United States
Environmental Protection
Agency

EPA 542-B-94-002
April 1995

Solid Waste and Emergency Response (5102W)

Innovative Site Remediation Technology

Vacuum Vapor Extraction
Volume 8

U.S. Environmental Protection Agency
Region 5, Library (PL-12J)
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INNOVATIVE SITE REMEDIATION TECHNOLOGY

VACUUM VAPOR EXTRACTION

One of an Eight-Volume Series

Edited by
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1994

Prepared by WASTECH®, a multiorganization cooperative project managed by the American Academy of Environmental Engineers® with grant assistance from the U.S. Environmental Protection Agency, the U.S. Department of Defense, and the U.S. Department of Energy.

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Library of Congress Cataloging in Publication Data

Innovative site remediation technology/ edited by William C. Anderson
224 p. 15.24 x 22.86cm.
Includes bibliographic references.
Contents: -- [2] Chemical treatment -- [3] Soil washing/soil flushing
-- [4] Stabilization/solidification -- [6] Thermal desorption -- [7] Thermal destruction
[8] Vacuum vapor extraction
1. Soil remediation. I. Anderson, William, C., 1943- .
II. American Academy of Environmental Engineers. III. Johnson, Paul C., 1961- .
TD878.I55 1994 628.5'5 93-20786
ISBN 1-883767-02-4 (v. 2) ISBN 1-883767-06-7 (v. 6)
ISBN 1-883767-03-2 (v. 3) ISBN 1-883767-07-5 (v. 7)
ISBN 1-883767-04-0 (v. 4) ISBN 1-883767-08-3 (v. 8)

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Book design by Lori Imhoff

Printed in the United States of America

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The Air & Waste Management Association is a nonprofit technical and educational organization with more than 14,000 members in more than fifty countries. Founded in 1907, the Association provides a neutral forum where all viewpoints of an environmental management issue (technical, scientific, economic, social, political, and public health) receive equal consideration.

This worldwide network represents many disciplines: physical and social sciences, health and medicine, engineering, law, and management. The Association serves its membership by promoting environmental responsibility and providing technical and managerial leadership in the fields of air and waste management. Dedication to these objectives enables the Association to work towards its goal: a cleaner environment.

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The Hazardous Waste Action Coalition (HWAC) is an association dedicated to promoting an understanding of the state of the hazardous waste practice and related business issues. Our member firms are engineering and science firms that employ nearly 75,000 of this country's engineers, scientists, geologists, hydrogeologists, toxicologists, chemists, biologists, and others who solve hazardous waste problems as a professional service. HWAC is pleased to endorse the monograph as technically sound.

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ACKNOWLEDGMENTS

The WASTECH® project was conducted under a cooperative agreement between the American Academy of Environmental Engineers® and the Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. The substantial assistance of the staff of the Technology Innovation Office was invaluable.

Financial support was provided by the U.S. Environmental Protection Agency, Department of Defense, Department of Energy, and the American Academy of Environmental Engineers®.

This multiorganization effort involving a large number of diverse professionals and substantial effort in coordinating meetings, facilitating communications, and editing and preparing multiple drafts was made possible by a dedicated staff provided by the American Academy of Environmental Engineers® consisting of:

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1 INTRODUCTION

This monograph on vacuum vapor extraction is one of a series of eight on innovative site and waste remediation technologies that are the culmination of a multiorganization effort involving more than 100 experts over a two-year period. It provides the experienced, practicing professional guidance on the application of innovative processes considered ready for full-scale application. Other monographs in this series address bioremediation, chemical treatment, solvent/chemical extraction, soil washing/soil flushing, stabilization/solidification, thermal desorption, and thermal destruction.

1.1 Vacuum Vapor Extraction

A basic in situ vapor (or soil vapor) extraction system couples vapor extraction wells with blowers or vacuum pumps to remove contaminant vapors from zones permeable to vapor flow, thereby enhancing the volatilization and removal of contaminants from the subsurface for treatment, as appropriate. The vacuum developed in the extraction well boring results in air being drawn from the atmosphere through the soil to the well. More complex soil vapor extraction systems incorporate trenches, horizontal wells, forced-air injection wells, passive air inlet wells, groundwater recovery systems, impermeable surface seals, multiple vapor extraction wells in single boreholes, and various thermal enhancements. Soil vapor extraction can also be practiced ex situ with excavated soils; perforated pipes are placed within soil piles to produce air movement through the pile.

In addition to vapor extraction, the monograph addresses complementary technologies – air sparging (injecting air under pressure below the water table) and bioventing (applying air in the course of vapor extraction into the subsurface to accelerate aerobic biodegradation).

1.2 Development of the Monograph

1.2.1 Background

Acting upon its commitment to develop innovative treatment technologies for the remediation of hazardous waste sites and contaminated soils and groundwater, the U.S. Environmental Protection Agency (US EPA) established the Technology Innovation Office (TIO) in the Office of Solid Waste and Emergency Response in March, 1990. The mission assigned TIO was to foster greater use of innovative technologies.

In October of that same year, TIO, in conjunction with the National Advisory Council on Environmental Policy and Technology, convened a workshop for representatives of consulting engineering firms, professional societies, research organizations, and state agencies involved in site remediation. The workshop focused on defining the barriers that were impeding the application of innovative technologies in site remediation projects. One of the major impediments identified was the lack of reliable data on the performance, design parameters, and costs of innovative processes.

The need for reliable information led TIO to approach the American Academy of Environmental Engineers®. The Academy is a long-standing, multidisciplinary environmental engineering professional society with wide-ranging affiliations with the remediation and waste treatment professional communities. By June 1991, an agreement in principle (later formalized as a Cooperative Agreement) was reached. The Academy would manage a project to develop monographs describing the state of available innovative remediation technologies. Financial support would be provided by the EPA, U.S. Department of Defense (DOD), U.S. Department of Energy (DOE), and the Academy. The goal of both TIO and the Academy was to develop monographs providing reliable data that would be broadly recognized and accepted by the professional community, thereby, eliminating or, at least, minimizing this impediment to the use of innovative technologies.

The Academy's strategy for achieving the goal was founded on a multiorganization effort, WASTECH®(pronounced Waste Tech), which joined in partnership the Air and Waste Management Association, the American Institute of Chemical Engineers, the American Society of Civil Engineers, the American Society of Mechanical Engineers, the Hazardous

Waste Action Coalition, the Society for Industrial Microbiology, and the Water Environment Federation, together with the Academy, EPA, DOD, and DOE. A Steering Committee composed of highly respected representatives of these organizations having expertise in remediation technology formulated the specific project objectives and process for developing the monographs (see page iv for a listing of Steering Committee members).

By the end of 1991, the Steering Committee had organized the Project. Preparation of the monograph began in earnest in January, 1992.

1.2.2 Process

The Steering Committee decided upon the technologies, or technological areas, to be covered by each monograph, the monographs' general scope, and the process for their development and appointed a task group composed of five or more experts to write a manuscript for each monograph. The task groups were appointed with a view to balancing the interests of the groups principally concerned with the application of innovative site and waste remediation technologies — industry, consulting engineers, research, academe, and government (see page iii for a listing of members of the Vacuum Vapor Extraction Task Group).

The Steering Committee called upon the task groups to examine and analyze all pertinent information available, within the Project's financial and time constraints. This included, but was not limited to, the comprehensive data on remediation technologies compiled by EPA, the store of information possessed by the task groups' members, that of other experts willing to voluntarily contribute their knowledge, and information supplied by process vendors.

To develop broad, consensus-based monographs, the Steering Committee prescribed a twofold peer review of the first drafts. One review was conducted by the Steering Committee itself, employing panels consisting of two members of the Committee supplemented by at least four other experts (see *Reviewers,* page iii, for the panel that reviewed this monograph). Simultaneous with the Steering Committee's review, each of the professional and technical organizations represented in the Project reviewed those monographs addressing technologies in which it has substantial interest and competence. Aided by a Symposium sponsored by the Academy in October 1992, persons having interest in the technologies were encouraged to participate in the organizations' review.

Comments resulting from both reviews were considered by the Task Group, appropriate adjustments were made, and a second draft published. The second draft was accepted by the Steering committee and participating organizations. The statements of the organizations that formally reviewed this monograph are presented under *Reviewing Organizations* on page v.

1.3 Purpose

The purpose of this monograph is to further the use of innovative site remediation technologies, i.e., technologies not commonly applied, where their use can provide better, more cost-effective performance than conventional methods. To this end, the monograph documents the current state of vacuum vapor extraction and of the complementary technologies, air sparging and bioventing, as they relate to it.

1.4 Objectives

The monograph's principal objective is to furnish guidance for experienced, practicing professionals and users' project managers. The monograph is intended, therefore, not to be prescriptive, but supportive. It is intended to aid experienced professionals in applying their judgment in deciding whether and how to apply the technologies addressed under the particular circumstances confronted.

In addition, the monograph is intended to inform regulatory agency personnel and the public about the conditions under which the processes it addresses are potentially applicable.

1.5 Scope

The monograph addresses vacuum vapor extraction and other complementary innovative technologies. It addresses all aspects of the technolo-

gies for which sufficient relevant data was available to the Vacuum Vapor Extraction Task Group to describe and explain the technologies and assess their effectiveness, limitations, and potential applications. Laboratory- and pilot-scale technologies were addressed, as appropriate.

Application of site remediation and waste treatment technology is site specific and involves consideration of a number of matters besides alternative technologies. Among them are the following that are addressed only to the extent essential to understand the applications and limitations of the technologies described:

- site investigations and assessments;
- planning, management, specifications, and procurement; and
- regulatory requirements.

1.6 Limitations

The information presented in this monograph has been prepared in accordance with generally recognized engineering principles and practices and is for general information only. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application.

Readers are cautioned that the information presented is that which was generally available during the period when the monograph was prepared. Development of innovative site remediation and waste treatment technologies is ongoing. Accordingly, postpublication information may amplify, alter, or render obsolete the information about the processes addressed.

This monograph is not intended to be and should not be construed as a standard of any of the organizations associated with the WASTECH® Project; nor does reference in this publication to any specific method, product, process, or service constitute or imply an endorsement, recommendation, or warranty thereof.

1.7 Organization

This monograph and others in the series are organized under a uniform outline intended to facilitate cross reference among them and comparison of the technologies they address. Chapter 2.0, Process Summary, provides an overview of all material presented. Chapter 3.0, Process Identification, provides comprehensive information on the process addressed and fully analyzes it. The analysis includes, to the extent information and data are available, a description of the process (what it does and how it does it), its scientific basis, status of development, environmental effects, pre- and post-treatment requirements, health and safety considerations, design data, operational considerations, and comparative cost data. Also addressed are process-unique planning and management requirements and process variations. Chapter 3.0 and subsequent chapters focus upon the principal technology, vapor extraction, and address the complementary technologies, air sparging and bioventing, where appropriate.

Chapter 4.0, Potential Applications, Chapter 5.0, Process Evaluation, and Chapter 6.0, Limitations, provide syntheses of available information and informed judgments on the process. Each of these chapters addresses the process in the same order as it is described in Chapter 3.0. Technology Prognosis, Chapter 7.0, identifies aspects of the process needing further research and demonstration before full-scale application can be considered.

2
PROCESS SUMMARY

2.1 A History of Soil Vapor Extraction

Although articles relating to soil vapor extraction began to appear in journals and conference proceedings in the early 1980s, soil vapor extraction is no different in principle from the vapor abatement processes practiced much earlier for the control of volatile organic compound (VOC) migration into buildings. The majority of early articles are anecdotal reports of field applications, many of which have been summarized by Hutzler, Murphy, and Gierke (1989). Many of the sites treated were gasoline or solvent spills in relatively pervious sands. The process was nearly always reported to be successful, but appropriate monitoring and system controls were frequently absent and final cleanup levels were rarely reported, if determined.

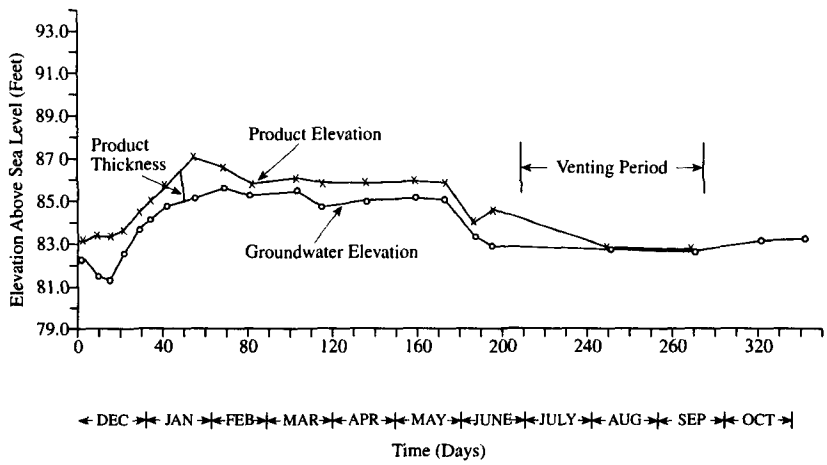
The transition from the use of soil vapor extraction as a vapor abatement technology to the process now used to remove nonaqueous phase liquids (NAPL's) is clearly documented in the literature through the contributions of the Texas Research Institute (1980) and Thornton and Wootan (1982). They introduced the concept of vertical vapor extraction and injection wells for the removal of residual hydrocarbon (gasoline product, as well as consequential gasoline compounds in the gas phase) and the use of vapor probes for sampling and qualitative and quantitative analysis of the diffused gasoline hydrocarbon vapors. A further enhancement of this research entailed hypothesizing of various venting geometries and subsequent air-flow paths and their testing in a pilot-scale soil tank (Texas Research Institute 1984). In the Institute's first study (1980), 50% removal of gasoline was achieved by means of soil vapor extraction. In its second study (1984), 84% of the

gasoline product was removed; however, it was believed that up to 30% of the gasoline may have been removed through stimulated biological activity.

Encouraged by results of the Texas Research Institute's research, Marley and Hoag (1984) and Marley (1985) conducted laboratory soil column experiments and demonstrated that all of the gasoline at residual saturation could be removed using soil vapor extraction sands in the range from 0.224 mm to 2.189 mm (0.009 to 0.086 in.) average diameter at air-flow rates from 16.1 cm^3/cm^2-min to 112.5 cm^3/cm^2-min (0.53 to 3.7 ft^3/ft^2-min).

This was followed by the field study of Hoag and Cliff (1988), who reported that an in situ soil vapor extraction system was able to remove 1,330 L (350 gal) of gasoline at residual saturation and at the capillary fringe in 100 days. Cleanup levels of below 3 ppm_v were reported using GC/FID analysis of soil-gas samples. Groundwater elevation and product thickness were logged for a substantial period before and after the application of soil vapor extraction. Figure 2.1 is a well log of one of the monitoring wells at the site. One-to-two feet of gasoline product persisted in the

Figure 2.1
Groundwater and Free-Product Elevations Prior to and During a Vapor Extraction Application



Source: Hoag and Cliff 1988

well for a period of approximately 210 days. By day 250 (40 days of soil vapor extraction), the product thickness was not measurable and only a skim was detected on the water table. After day 290 (80 days of soil vapor extraction), no skim of gasoline was detected. Thus, soil vapor extraction was effective in removing both gasoline at residual saturation and as free product on the water table.

In one of the first attempts to model the fundamental processes governing soil vapor extraction performance, Marley and Hoag (1984), using Raoult's Law to predict the concentration and composition of extracted air and 52 compounds in gasoline as an approximate composition, developed an equilibrium-based model describing residual hydrocarbon-gas phase interaction during the soil vapor extraction column tests. This work was further advanced by Baehr and Hoag (1988) who developed a coupled one-dimensional compressible air flow, three-phase local-equilibrium based model to describe the results of the Marley (1985) soil vapor extraction column tests. These equilibrium-based modeling approaches have also been used successfully by Johnson, Kemblowski, and Colthart (1988), Johnson, Kemblowski, and Colthart (1990), and Johnson et al. (1991). Other screening level approaches have been used to assess vapor-flow dynamics and mass transport considerations (Massmann 1989; Johnson, Kemblowski, and Colthart 1988; Johnson et al. 1990, 1991; Shan, Falta, and Javandel 1992). More sophisticated levels of modeling have been recently advanced by others; these are discussed in Section 3.2.

2.1.1 Soil Vapor Extraction

A typical in situ soil vapor extraction system couples vapor extraction wells with blowers or vacuum pumps to remove contaminant vapors from zones permeable to vapor flow, thereby enhancing the volatilization and efficiency of removal of contaminants from the subsurface. The components of soil vapor extraction systems are usually available off-the-shelf. Qualified engineering firms can install the necessary wells and trenches. Aboveground equipment usually consists of:

- vacuum blower and controls;
- control valves to adjust air flow;
- pressure gauges and flow meters at wellheads;

- air-liquid separator (for removing moisture from the extracted gases);
- pressure gauge and flow meter at the pump; and
- vapor treatment unit.

If air treatment is required, vapor treatment systems, such as catalytic or thermal destruction systems, activated carbon adsorbers, or biological gas treatment systems are employed.

Soil vapor extraction can be employed ex situ for treating excavated soils. In this scenario, perforated pipes are placed within soil piles to draw air through the pile. The equipment is the same as that used for in situ applications.

Although the equipment and process are relatively simple, the design, operation, and monitoring of soil vapor extraction systems are not. The central questions of cost-effectiveness and practicability may be quite complex and subject to a high degree of uncertainty. Determining optimal design criteria – the number, location, spacing, and construction of extraction/injection wells, vapor treatment systems, degree of operational control, and requisite monitoring – is frequently difficult. In practice, soil vapor extraction is often limited by such factors as the equipment available, the contaminant(s) of concern, site conditions (geology, location and construction of buildings, etc.) and regulatory cleanup criteria.

2.1.2 Air Sparging

Air sparging, a more recent innovation, may extend the application of soil vapor extraction to water-saturated soils. The technology, which is still emerging, has been applied at sites contaminated with chlorinated solvents, gasoline, and aviation fuel.

Air sparging is accomplished by injecting air under pressure below the water table. It is expected that contaminants located within air-flow pathways will volatilize or biodegrade and there is the potential that dissolved-phase contaminants that contact the air-flow field could potentially be volatilized or biodegraded.

Two theories have been advanced to explain the effect of air sparging:

- injected air strips contaminants from the soil and groundwater into the vapor flow; and

- injected air increases the oxygen content of the groundwater, resulting in increased aerobic biodegradation.

It is likely that both contribute to remediation at all sites. Improperly controlled air sparging systems can pose significant health and safety risks. The pressurized air can accelerate the uncontrolled migration of contaminant vapors and the consequent accumulation in buildings or other vapor receptors. It has been suggested that there may also be the potential for enhanced spreading of dissolved contaminant plumes as the injected air initially displaces groundwater. In addition, it has been suggested that the air injection may result in increased mixing and, therefore, increased mass transfer of contaminants into groundwater. To minimize the risk of uncontrolled vapor or groundwater migration components, the following measures should be considered for effective and safe operation:

- concurrent installation of a soil vapor extraction system to capture the entire volume of contaminant vapors; and
- containment of groundwater in the air injection zone to prevent off-site migration of dissolved contaminants.

In addition to the health and safety risks, another concern is that air sparging may lead to modified aquifer conditions such as aquifer plugging because of iron precipitation stimulated by increased oxygen levels.

2.1.3 Bioventing

Numerous investigations have shown that many contaminants of concern are biodegradable and indigenous microorganism populations can carry out the remediation task if subsurface conditions are amenable. The microbes utilize oxygen to break down hydrocarbons into carbon dioxide, water, and biomass (cells) and, under natural conditions, aerobic biodegradation rates are typically limited by oxygen supply rates in the subsurface. But in the course of vapor extraction, air is drawn from the atmosphere into the subsurface, and accelerates the resupply of oxygen. Several researchers have shown that this enhanced oxygen delivery will affect an increase in the rate of aerobic biodegradation of contaminants.

Bioventing is still under development, but has been used to remediate sites where various fuels and nonchlorinated compounds have been released. Various bioventing configurations have been proposed, two of which are illustrated in figure 3.7 on page 3.15.

By monitoring oxygen utilization and carbon dioxide production aerobic biodegradation rates can be estimated. In bioventing, the object is to optimize biodegradation rates. This often requires maintaining the oxygen content of the soil at some set value (2 to 4% v/v, note: % v/v is % volume to volume and is the equivalent of % by volume). Bioventing is also affected by other site conditions. Low soil moisture content and low temperature can slow microbial degradation, while gentle heating of the soil to 30° to 40°C (86° to 104°F) and increasing moisture content can enhance biological activity.

Engineered bioventing systems can offer capital equipment and operating and maintenance cost reductions by utilizing lower air flows and eliminating the need for vapor treatment equipment.

In a bioventing application, lower airflow rates frequently reduce operation, monitoring, and maintenance costs on a daily basis, but they can increase the time required for cleanup. The net impact on cost depends on site-specific factors.

It should be noted that bioventing has recently evolved into a more widely applied technology in its own right. This manuscript was prepared initially in 1992, and at that time the decision was made to discuss bioventing as it applies to soil vacuum extraction applications. The manuscript subsequently has undergone review and limited modification, but the emphasis has not changed. More detailed manuals specifically addressing bioventing are in preparation.

2.1.4 Thermal Enhancements of Soil Vapor Extraction

It is generally accepted that soil vapor extraction becomes less effective where compounds have vapor pressures less than 0.1 mm Hg to 1.0 mm Hg at ambient temperatures. It is believed, however, that the range of applicability can be extended by heating the subsurface because contaminant vapor pressures increase with temperature. Also, biodegradation can be increased by warming the subsurface to temperatures in the range of 30° to 40°C (86° to 104°F).

There are a number of in situ heating processes under study. These include steam injection, hot air injection, electrical resistance heating, radio-frequency heating, thermal conduction heating, warm water injection, and solar heating. Each combines conventional vapor extraction equipment

with a means to elevate the subsurface temperature. Most of these technologies are still under development, although steam injection has been used extensively by the petroleum industry.

There are several limitations in applying thermal enhancement technologies. Generation of excessive soil temperatures inhibits biodegradation and affects soil structure. Some thermal enhancement processes entail large capital equipment and energy costs.

Pertinent to steam injection, contaminants in the soil may vaporize and become dissolved in the condensate front or be displaced. Heterogeneities in the geological formations and in the contamination can decrease the process's effectiveness. The process must be properly controlled in order to minimize possible detrimental effects, such as contaminant "smearing" or enhanced vapor transport away from the source area.

2.2 Fundamentals and Basic Phenomena

The basic phenomena governing the performance of soil vapor extraction systems are easily described. Applying a vacuum to an extraction well creates an air-flow field that originates at the ground surface and proceeds along the path of least resistance (i.e., highest permeability to air flow) to the screened interval of the extraction well. Contaminants volatilize within the air-flow field, are swept into the vapor extraction well, and removed from the soil. Once these vapors are removed, additional contaminants outside the flow field volatilize, diffuse to the air-flow field, and are removed from the soil. Ideally, residual contaminant volatilization and removal occur continuously until all of the residual contaminant in the unsaturated zone and above the capillary fringe is removed from the soil.

The performance of all vapor extraction-based processes can be related to three main factors:

- equilibrium partitioning into the vapor space of a porous medium;
- vapor flow characteristics of the porous medium; and
- mass transfer (kinetic) considerations and limitations (e.g., processes that prevent equilibrium from being achieved).

2.3 System Design

Competent characterization of the site and contaminants present is necessary in order to assess the feasibility of vapor extraction-based technologies and design effective remedial systems. See table 3.3 on page 3.57 for an outline of essential site characterization activities.

System designs and matching system components with remedial objectives is only the first step in successful application of this technology. Because of compounding uncertainties and inherent limitations arising from natural heterogeneities, site characterization data, and predictive capabilities, the design and optimization of vapor extraction-based processes continues even after the initial system is installed and turned on. As with all engineered systems, system performance must be monitored correctly, the results must be interpreted, and system modifications must be made accordingly. Therefore, vapor extraction-based systems should be flexible in design so that they can handle a wide range of modifications and operating conditions.

Along with the operating conditions, the following components are typically specified in a soil vapor extraction-based system design:

- number of vapor extraction wells;
- number of air injection wells (not at all sites);
- well location(s);
- well construction(s) (depth, screened interval, materials, etc.);
- extraction blower(s) or vacuum pump(s);
- injection blower(s) (not at all sites);
- vapor treatment unit(s);
- equipment manifolding & piping;
- instrumentation (flow meters, sampling ports, vapor concentration monitoring, etc.); and
- monitoring program/target remediation goals.

2.4 Costs

Like other in situ technologies, the cost of vapor extraction-based processes is not easily quoted per volume of soil treated as is done for many ex situ processes (incineration, thermal desorption, soil washing, etc.), as useful as that would be, because of large variations in site geology, type of contaminant, etc. Also, these technologies are very sensitive to depth to contamination. For example, clean overburden soil must be excavated to remove contaminated soil and this affects the total cost. However, fairly educated estimates can be made for major capital equipment costs and these have been set forth, where appropriate, in subsequent chapters. The major part of the total process cost associated with vapor extraction-based processes is usually the operating expenses for labor, maintenance, and monitoring.

2.5 Performance Monitoring

Performance data are monitored in order to assess performance, calibrate models, and help guide needed system modifications resulting from changes in operating conditions. There is a wide range of process monitoring options from which the practitioner can select depending upon the particular need for data. See table 3.7 on page 3.109, listing options in order of importance.

2.6 Potential Applications

Case studies and guidance documents indicate that vapor extraction-based technologies are most likely to be successful at sites where volatile compounds have impacted permeable soils. Typically, sites considered for vapor extraction-based technologies are those where petroleum products (e.g., gasoline and other fuels) or chlorinated solvents have spilled or leaked into the subsurface. This guidance, however, is intended only to roughly define the range of applicability, rather than to limit it. Remedial goals

consist of target cleanup levels and an acceptable time frame for remediation. The goals are based on considerations of risk and of the potential for preserving reasonable beneficial use. Typical constraints include total project cost, technical feasibility, permitting requirements, physical boundaries, community-imposed limitations, and equipment availability. Site-specific data, including those on geological conditions and contaminant characteristics, are also considered, along with pilot-test data, if available.

2.7 Process Evaluation

For properly designed systems, removal rates are highest when the system is first turned on. The rates then decline over time, and often reach very low levels, often called "asymptotic". It should be noted that the removal rates do not follow the strict definition of asymptotic, as they will probably continue to decline very slowly. However, for practical engineering purposes, we can think of them as asymptotic.

The practicable degree of remediation that can be achieved with vapor extraction-based technologies is limited by site characteristics and contaminant properties. The actual degree of remediation that can be achieved, however, depends also on the skill and knowledge of the practitioner, which is reflected in system design and operation. Inefficient remedial operations may appear to be highly successful in the eyes of untrained practitioners. Against this background, unfortunately, adequately documented case studies are not available that clearly demonstrate the results of vapor extraction-based processes. Most case studies fail to report final soil and groundwater contaminant levels, costs, and original target cleanup levels. In general, the case studies fail to state what triggered the decision to turn the system off and whether the cleanup goals were achieved. It is difficult, therefore, to judge whether the application was "successful."

Process monitoring does not always indicate when cleanup goals have been reached. Some vendors claim that vapor extraction cleanups occur in fewer than 90 days at some sites. In the authors' experience, however, most systems installed at commercial gasoline service stations operate for one to five years.

Ultimately, soil and groundwater sampling are required to verify cleanup. Soil sampling should be performed when contaminant and respiratory gas concentrations approach background levels, no significant restart spike is observed, and oxygen utilization does not exceed background. Many closure plans include a minimum one year period of posttreatment vapor and groundwater monitoring in both vadose and saturated zones to demonstrate long-term effectiveness. An endpoint can also sometimes be negotiated based on economic analysis, i.e., when a predetermined cost per unit contaminant removed is reached and operations are halted.

2.8 Prognosis

Of the vapor extraction-based technologies, soil vapor extraction has been practiced longest and at the most sites. Laboratory and modeling studies have contributed a basic understanding of the processes involved in system performance. Even with this seemingly mature process, however, there is room for improving system performance and reducing costs. Engineering analysis is required to assess the feasibility of vapor extraction-based processes, interpret field test results, design systems, and optimize system performance. Engineering analysis (design equations, computer programs, etc.) could help reduce uncertainty in predictions of system performance and cost. It could also supplement field experience by allowing practitioners to predict what will happen at one site based on appropriate applications of models and observations at other similar sites.

Air sparging and bioventing are promising emerging technologies at different stages of development. A realistic niche has been identified for each, but the site remediation industry has little practical experience with them. Other vapor extraction-based processes, such as in situ soil heating, are still considered experimental.

3

PROCESS IDENTIFICATION AND DESCRIPTION

Recently, in situ subsurface remediation processes have gained considerable attention among practitioners and researchers concerned with the remediation of sites contaminated with volatile and semivolatile organic compounds (VOCs and SVOCs). Of the in situ processes available, soil vapor extraction has the greatest potential for widespread application in the remediation of these sites. In addition, a number of complementary technologies such as air sparging, bioventing, subsurface heating, and aboveground soil treatment using soil piles, are applied using soil vapor extraction as the central remedy. Their application holds promise of remediating sites having difficult geology or compounds in the subsurface not fully removable by soil vapor extraction alone. At the time of writing this document, the states-of-the-art and practice are both clearly more developed for in situ soil vapor extraction applications than for the complementary vapor extraction-based technologies. Therefore, emphasis will be placed in this monograph on soil vapor extraction, while certain of the complementary technologies will be addressed to the extent necessary to reflect both the states-of-the-art and practice of soil vapor extraction.

According to the United States Environmental Protection Agency (US EPA) the use of soil vapor extraction has dramatically increased in the past few years. Based on US EPA's Superfund Remedial Action Records of Decision (ROD) involving innovative treatment technologies as of June 1993, 202 were based on treatment (US EPA 1993). Of these, 107 cited soil vapor extraction, while the next most frequently cited technologies were bioremediation with 60 and thermal desorption with 32. The selection of soil vapor extraction for Superfund sites increased 45% in federal fiscal year 1991 over 1990. As of February 1992, soil vapor extraction had been the most frequently selected source control technology under the entire Superfund Program, representing 40% of all technologies at predesign

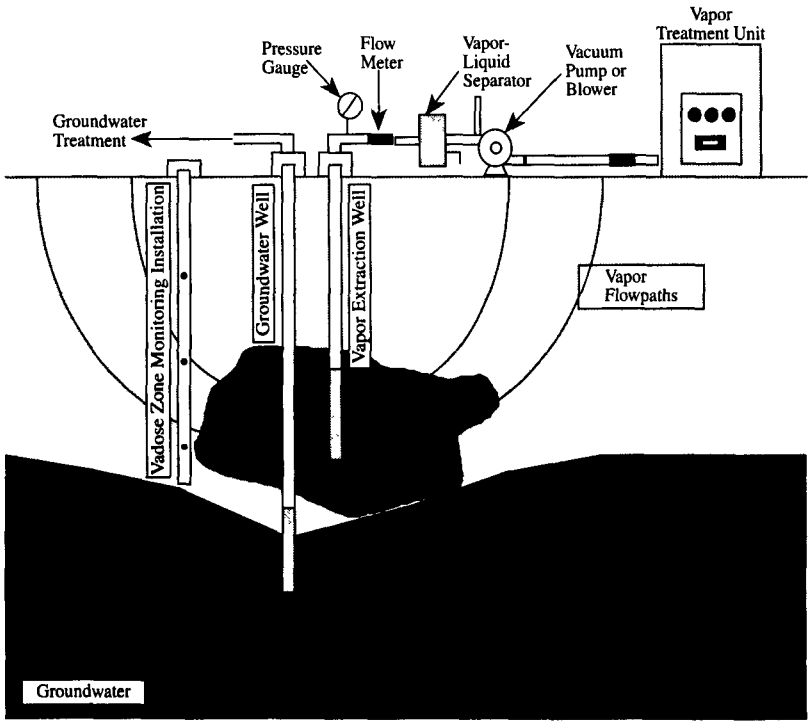
through completion stages. The inherent flexibility of soil vapor extraction in application, the nature of the technology, and its ability to complement other source control technologies have resulted in its increasing use as a remedial technology.

3.1 Description of the Technologies

3.1.1 Soil Vapor Extraction

A basic in situ soil vapor extraction system, such as the one depicted in figure 3.1a (on page 3.3), couples vapor extraction wells with blowers or vacuum pumps to remove contaminant vapors from zones permeable to vapor flow, thereby enhancing the volatilization and removal of contaminant from the subsurface. The vacuum developed through a screened casing in the extraction well boring results in air being drawn from the atmosphere through the soil to the well. Aboveground equipment often consists of blower(s) or vacuum pump(s), control valves to adjust airflow (particularly useful in multiple well, single pump applications), pressure gauges and flow meters at wellheads, an air-liquid separator (for removal of moisture from the extracted gases), a pressure gauge and flow meter at the pump, and a vapor treatment unit. Vapor treatment systems such as catalytic and thermal destruction systems, activated carbon adsorbers, and biological gas treatment systems, are included if air treatment is required. Air discharge stacks may be adequate where it can be demonstrated that subsequent dispersion of the vapors reduces their concentrations to acceptable levels. Also shown in figure 3.1a is a groundwater pump and skim well, which is one method to access residual contaminants that are trapped below the normal groundwater level. When this occurs, the groundwater recovery well is used to depress the water table, thereby exposing previously water-saturated soils to vapor flow. More complex soil vapor extraction systems incorporate trenches, horizontal wells, forced-air injection wells, passive air inlet wells, low permeability or impermeable surface seals, multiple level vapor extraction wells in single boreholes, and sophisticated unsaturated zone moisture, contaminant, and temperature monitoring systems.

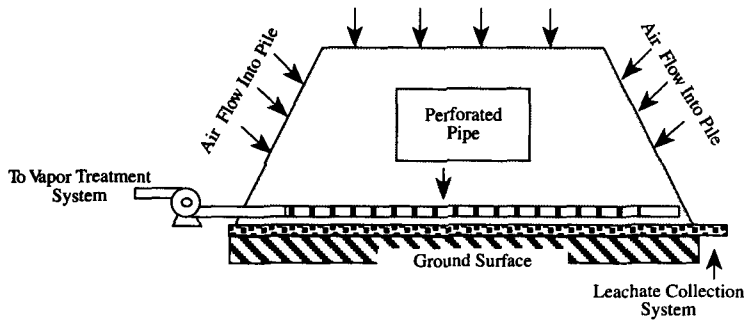
Figure 3.1a
Simplified In Situ Soil Vapor Extraction Schematic



Soil vapor extraction can also be practiced ex situ in excavated soils; perforated pipes are placed within soil piles to draw air through the pile, as shown in figure 3.1b (on page 3.4). The equipment (blowers, vapor treatment, etc.) is the same as that used in in situ applications.

The above-ground components of soil vapor extraction systems are typically off-the-shelf items, and qualified engineering firms can install wells and trenches. Some large-scale applications may require firms experienced in managing large construction projects, particularly where there are trenches or aboveground applications. Despite the seeming simplistic nature of the process and equipment, effective design, operation, monitoring, and optimization of soil vapor extraction systems requires a thorough un-

Figure 3.1b
Simplified Ex Situ Soil Vapor Extraction Schematic

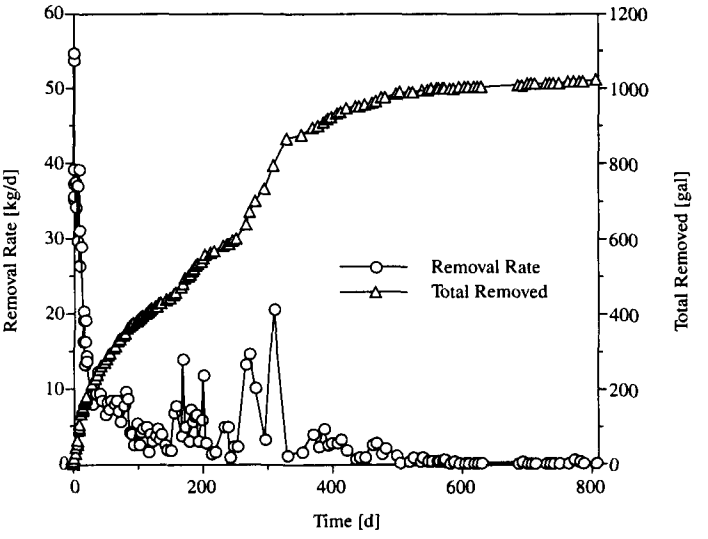


derstanding of the governing phenomena. The basic issue of assessing soil vapor extraction feasibility for any given site is itself attended by a great degree of uncertainty. And, if one selects soil vapor extraction, design criteria, involving the number, location, spacing, and construction of the extraction/injection wells, vapor treatment systems, appropriate degree of operational control, and requisite monitoring, can be difficult to determine. In this monograph, an attempt will be made to compare and contrast the states-of-the-practice and art of soil vapor extraction feasibility screening, design, and operation.

Figure 3.2 (on page 3.5) provides a representative performance curve (actual removal rates and time scales vary from site to site). Removal rates of properly designed systems are highest when the system is first turned on. They then decline over time and often reach an apparent asymptotic limit that may be indicative of either mass reduction, compositional changes in the residual hydrocarbon, or mass-transfer limitations (see Subsections 3.2.9 and 3.2.11).

As a result of experimental and theoretical investigations, the basic phenomena governing performance of soil vapor extraction systems can be readily explained. The application of a vacuum to an extraction well creates an air-flow field that originates at the ground surface and proceeds preferentially along the path of least resistance (highest permeability to air flow) to the screened interval of the extraction well. Air still follows other

Figure 3.2
Typical Soil Vapor Extraction Performance Curves



Source: Johnson et al. 1991

paths but to a lesser degree. The air-flow field, shown in figure 3.1a (on page 3.3), has vertical and horizontal velocity components that are the result of the horizontal and vertical intrinsic permeabilities of the soil, k_v and k_h, and the relative permeability of the soil to air, which is a function of residual contaminant concentrations and soil moisture content. An additional factor that may influence the air-flow field induced by soil vapor extraction is the permeability of any surface material, k_s. The comparative permeability of the soil surface, k_s, or the vertical permeability, k_v, to that of the horizontal component of the subsurface soil, k_h, will determine the amount of leakage occurring near a vapor extraction well. Contaminant vapors generated from volatilization within the air-flow field are then swept into the vapor extraction well and removed from the soil. Additional contaminants outside the flow field volatilize, diffuse in the air-flow field, and are similarly removed from the soil. Ideally, this process of contaminant volatilization and removal from the subsurface is continuous until all of the

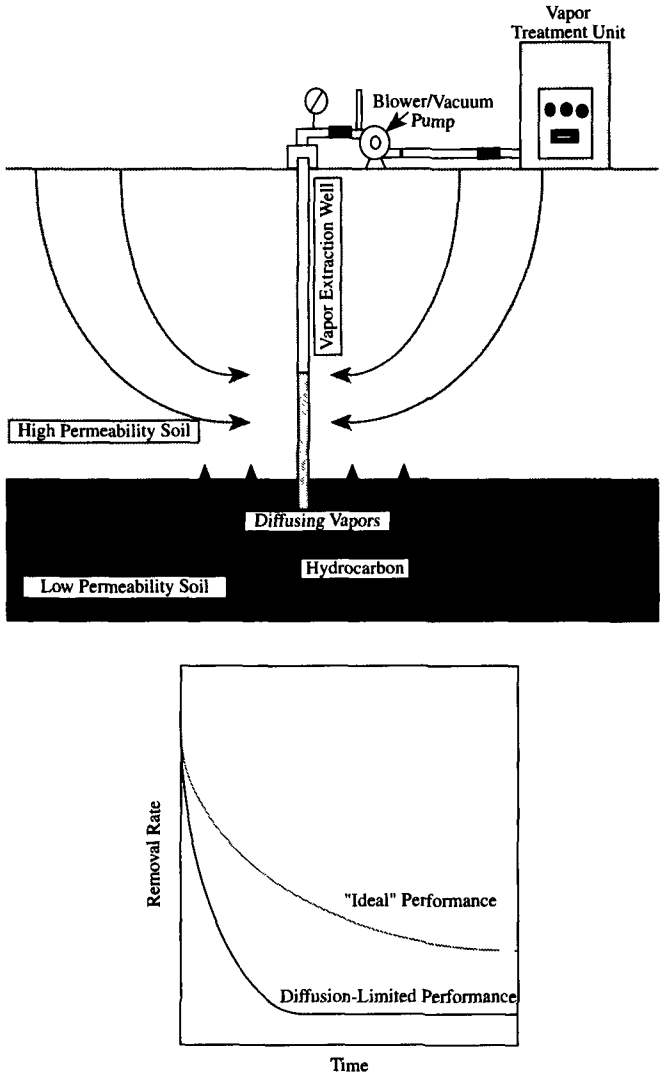
contaminant in the unsaturated zone and above the capillary fringe are removed from the soil.

It can readily be seen that a major goal of any vapor extraction operation is to induce air to flow through the zone of contamination, thereby creating ideal contact. When this occurs, vapors emanating from the residual contaminant do not need to diffuse a great distance to enter the air-flow field. On the other hand, if the air-flow field does not pass through the residual contaminant, but, for example, passes several feet above it, gas phase molecular diffusion will limit the rate of contaminant removal, as illustrated in figure 3.3 (on page 3.7). In this situation, the process could take orders of magnitude more time to remove residual contaminants than in the ideal case of a vapor flow passing through the contaminant zone. It follows, therefore, that the objective of a soil vapor extraction system is to minimize the length of the diffusion path the volatilized contaminants must take to enter the air-flow field. This can sometimes be accomplished by the addition of more wells or well screens placed at specific locations within the subsurface. It should be noted that microscale diffusion resistances (diffusion from within soil particles) may also limit vapor extraction performance.

Although many complex processes govern the behavior of air flow and contaminant interactions in the unsaturated zone, the three main factors that control performance of soil vapor extraction-based systems are the (1) chemical composition and characteristics of the contaminants to be removed, (2) air-flow rates achievable through the contaminated soil, and (3) air-flow path relative to the hydrocarbon distribution in the unsaturated zone. Following are some of the mechanisms controlling vapor removal from the unsaturated zone:

- gas advection;
- gas phase contaminant diffusion;
- sorption of residual contaminant and dissolved phase hydrocarbon on soil surfaces;
- chemical partitioning to the vapor phase;
- biological transformations;
- chemical transformations; and
- mass-transfer resistances controlling transport into the air-flow field.

Figure 3.3
Effect of Gas-Phase Diffusion Limitations on Performance



Although these mechanisms may affect the performance of a soil vapor extraction system, it may not always be feasible to quantify their effect.

3.1.2 Air Sparging

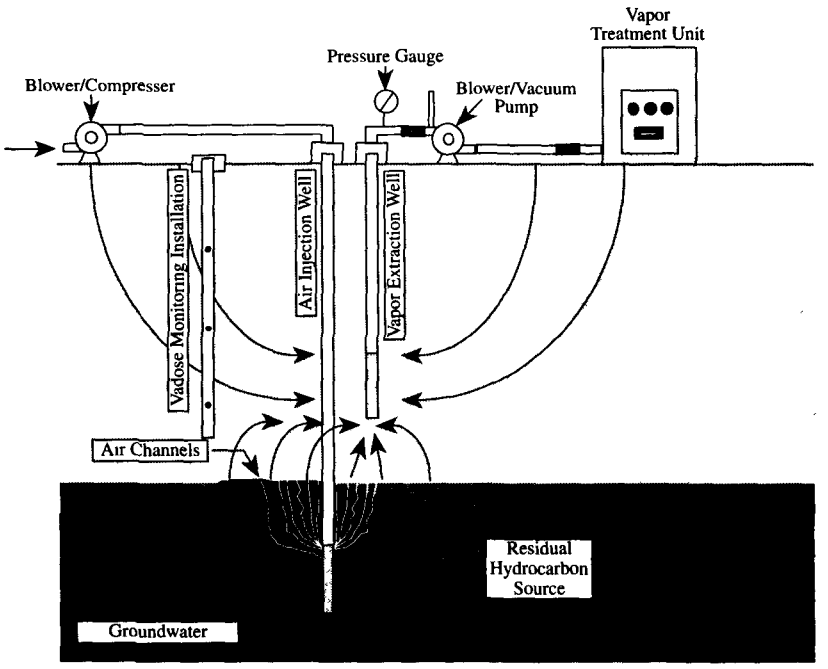
It should be evident that an inherent limitation of soil vapor extraction is that it will not remove contaminants that are beneath the unsaturated zone. In many cases, contaminants are released into the subsurface in such large quantities that the liquid migrates down to the saturated zone. Contaminant migration through the vadose zone and toward groundwater occurs through several mechanisms. Above the capillary fringe, the soil is only partially saturated with water and contaminants migrate principally by vapor diffusion, free-phase infiltration, and infiltration in solution. The majority of contaminant mass migrates in free-phase, but mass migrating by this mechanism is impeded in soil that is nearly saturated. This may occur in any wet zone in the vadose zone, but always becomes the case within the capillary fringe, which, depending on the soil and its capillary characteristics, may extend less than a meter to as much as ten meters above the static water table. Within the capillary fringe the free-phase contaminant accumulates in the non-saturated portions of soil. Monitoring wells within the zone typically show a layer of "pure" light non-aqueous phase liquid (LNAPL) floating on the groundwater, but the actual transition from LNAPL to groundwater in the subsurface is more gradual, with the capillary fringe representing a zone of partial water- and partial LNAPL-saturation. When the water table level fluctuates (because of seasonal or groundwater pumping changes), the contaminant becomes "smeared," or immobilized below the water table. If a basic soil vapor extraction system is used to remediate the smear zone, groundwater depression is necessary to expose the contaminant to vapor flow, as illustrated in figure 3.1a (on page 3.3). At some locations, however, depression of the water table may be impracticable. This is often the case in very permeable (high yield) aquifers, or very thick smear zones. Where dense nonaqueous phase liquids (DNAPLs) are present, the penetration to confining layers deep in the saturated zone may often preclude use of soil vapor extraction as the single treatment technology because of the inability to fully dewater the saturated zone.

Air sparging, a recent innovation, may be able to extend the utility of soil vapor extraction to water-saturated soils. Air is injected under pressure below the water table as shown in figure 3.4 (on page 3.9). It is commonly envisioned that injected air in the form of bubbles travels up through the

saturated zone, thereby transferring the hydrocarbons from the soil and groundwater phase into the vapor phase. It is more realistic, however, to expect continuous air channels to direct air flow in the saturated zone. In addition to volatilization, it is postulated that the injected air increases the oxygen resupply rate to the groundwater, resulting in increased aerobic biodegradation rates. Thus, there is some debate whether air sparging is primarily a volatilization-based process or simply an engineered bioremediation process. In figure 3.4, air injection wells are coupled with vapor extraction wells to assure that hydrocarbon vapors pushed into the unsaturated zone are recovered and handled appropriately aboveground.

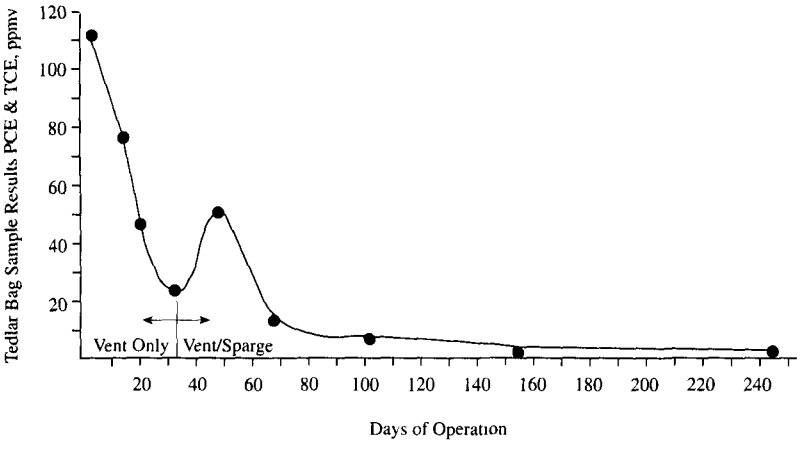
Once air is injected into the saturated zone, its advective flow is governed largely by the applied pressure, buoyant forces, vertical and horizon-

Figure 3.4
Simplified Air Sparging/Vapor Extraction Schematic



tal permeability distributions in the saturated zone, immiscible fluid displacement phenomena, and capillary properties of the soils. Depending on the size of the pores within the media, either air bubbles (extremely coarse materials) or continuous air channels (fine subsurface materials) form, providing a pathway for the injected air to the unsaturated zone. Significant channeling of the injected air may result from relatively minor heterogeneities in the saturated zone. It is expected that contaminants located within air-flow pathways will volatilize, and the potential exists for the stripping of dissolved-phase contaminants that contact the air-flow field. It is intended that air be injected to flow primarily through the area of contamination in the saturated zone as shown in figure 3.4 (on page 3.9); however, in view of the complex phenomena governing the injected air-flow field and the limited ability to characterize soil heterogeneities, there is a large degree of uncertainty *a priori* as to the true behavior of any air-sparging system design. Figure 3.5 provides sampling data indicating that operation of the air sparging system resulted in an initial doubling of the extracted vapor concentration from the soil vapor extraction system.

Figure 3.5
Extracted Vapor Concentrations for a Soil Venting/Air Sparging Application



Source: Brown, Henry, and Herman 1992

To the authors' knowledge, the first use of air sparging reported in the literature as a remedial technology was in an EPA office of Solid Waste and Emergency Response publication (US EPA 1988) for an installation in the Federal Republic of Germany (see also Bohler et al. 1990; and Middleton and Hiller 1990), mainly to treat groundwater contaminated with chlorinated solvents. It is likely to have been used prior to this time. The technology was later used in the U.S. to remediate gasoline-contaminated groundwater and soil in the saturated zone (Ardito and Billings 1990; Brown and Fraxedas 1991; and Marley 1991).

Although the use of air sparging has increased rapidly, considerable research and demonstration must be conducted before a consistent and reliable design approach can be realized and before a full understanding of its effectiveness and feasibility can be achieved.

As opposed to basic soil vapor extraction applications, improperly controlled air-sparging systems can create significant health and safety risks. This results from the introduction of pressurized air in the subsurface, which can accelerate the uncontrolled migration of hydrocarbon vapors, and the consequent accumulation in buildings, utility trenches, and other vapor receptors above and adjacent to the remediation area. In addition, the injected air initially displaces groundwater. Thus, there may be the potential for enhanced spreading of soluble hydrocarbon plumes. Another possible consequence is that air injection will result in increased mixing and, therefore, increased mass transfer of residual hydrocarbon components into dissolved and vapor phases. If the increased concentrations of these dissolved constituents are not captured in a pump-and-treat system or stripped by the injected air, it is possible that increases in groundwater concentrations could result. Safeguards, two of which are described below, should be considered to insure that these risks do not materialize:

- concurrent installation of a soil vapor extraction system to control the migration of contaminant vapors, except when degradation is significant enough to insure no impacts; and
- capture or containment of groundwater to prevent off-site migration of dissolved residual hydrocarbon components when sensitive receptors (e.g., domestic or public water supply wells) are nearby.

In addition to the health and safety concerns cited above, one should be aware of the potential for air sparging to result in modified aquifer condi-

tions, such as aquifer plugging because of iron precipitation or biomass growth stimulated by increased oxygen supply rate.

3.1.3 Bioventing

Under natural conditions aerobic biodegradation rates are typically limited by oxygen supply rates in the subsurface. But the rate of oxygen resupply to the subsurface is increased during the course of vapor extraction as air is drawn from the atmosphere into the subsurface. Consequently, it has been hypothesized that the enhanced oxygen delivery will affect an increase in aerobic biodegradation of hydrocarbons (Texas Research Institute 1980 and 1984; Wilson and Ward 1986; Bennedsen, Scott, and Hartley 1987; Conner 1988; and Ostendorf and Kampbell 1989). Field applications of soil vapor extraction conducted with the purpose of enhancing biodegradation have been reported by Ely and Heffner (1988), Staps (1989), and Hinchee et al. (1989). To fully mineralize a hydrocarbon such as benzene (convert to CO_2, H_2O, and biomass), a mass ratio of 3:1 g-oxygen/g-benzene is required. Alternate means of O_2 delivery have been considered, including addition as dissolved O_2 in water. However, assuming oxygen saturations of 8 mg/L O_2 for air-saturated water, 40 mg/L O_2 for pure O_2-saturated water, and 250 mg/L O_2 for a 500 mg/L H_2O_2 application, 2,000, 400, or 70 pore volumes of water, respectively, would be needed to fully mineralize about 1,000 mg/kg benzene in soil having a bulk density of 1,600 kg/m^3 (100 lb/ft^3) at a porosity of 30%. Relative to the use of water infiltration, inducing air flow is a significantly more efficient means to deliver O_2 to the unsaturated zone.

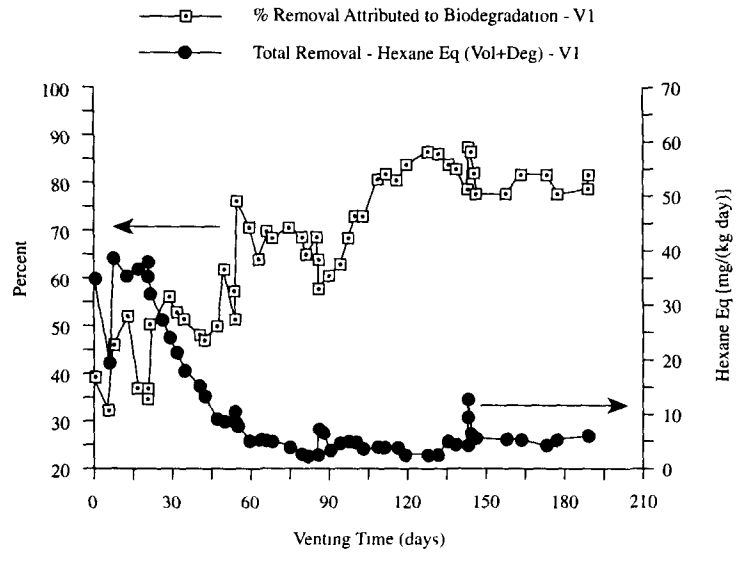
A by-product of the aerobic degradation of hydrocarbons is CO_2. Ely and Heffner (1988) observed that CO_2 was generated during soil vapor extraction; this was interpreted to be an indication of hydrocarbon degradation in the unsaturated zone. Furthermore, Kerfoot et al. (1988) and Woo and Coleman (1988) observed depressed O_2 and elevated CO_2 concentrations in soil-gas measurements taken at fuel hydrocarbon contaminated sites. It should be noted, however, that CO_2 may be produced by inorganic carbonate reactions; thus, one must be careful when inferring biodegradation rates from CO_2 measurements (Hinchee and Ong 1992). Smith, Dupont, and Hinchee (1991) reported that 50% of the approximately 40,000 kg (88,185 lb) of jet fuel removed from the subsurface at Hill Air Force Base, Utah, was removed by biological degradation, while the remainder was removed

by volatilization. Before bioventing, subsurface soil-gas oxygen concentrations in areas of high jet fuel contamination were less than 1%. Following a period of bioventing, much of the unsaturated zone formerly devoid of oxygen contained between 15 to 20% oxygen. In the initial period, the extraction rate averaged approximately 700 L/sec (1,500 ft^3/min), corresponding to about 15 to 20 void volume exchanges per day. Biodegradation in this period represented approximately 15% of total removal. This was followed by a period of lower airflow. Extraction averaged approximately 47 L/sec (100 ft^3/min) (representing $\approx$1 void volume exchange per day). Moisture and nutrient additions also were initiated during this period. During the low airflow rate period, volatilization declined greatly and biodegradation removal increased. The result was that biodegradation represented over 95% of the removal. Moisture addition did increase the rate of biodegradation, but it was not clear that nutrient addition had any beneficial effect (Dupont et al. 1991). To date, it has not been shown in a field study that nutrient addition has a beneficial effect on bioventing. Comparison of removal rates attributed to volatilization and biodegradation during a bioventing study at Tyndall Air Force Base, Florida, indicates that the mechanisms are of comparable effect (see figure 3.6 on page 3.14).

The physical setup for bioventing appears similar to standard vapor extraction configurations, but the objectives of the processes differ. In soil vapor extraction the goal is to maximize the rate of volatilization, which typically translates to maximization of vapor extraction rates. The goal of bioventing, however, is to optimize aerobic biodegradation. Operationally, this often requires maintaining the oxygen content in the soil at some set value (2 to 4% v/v); corresponding vapor-flow rates are then typically lower than in soil vapor extraction.

Various bioventing configurations have been proposed by Hinchee et al. (1989); two of these are illustrated in figure 3.7 (on page 3.15). Figure 3.7a presents a standard soil vapor extraction configuration wherein the extracted vapors are treated aboveground. The system shown in figure 3.7b is configured to eliminate the need for aboveground vapor treatment; the volatilized hydrocarbon vapors are drawn through a "clean" soil zone in the hope that they will be degraded in the subsurface before being extracted from it. In another configuration that does not use any vapor extraction wells (not shown), air is injected into the residual hydrocarbon zone at a controlled rate so that contaminant vapors are degraded as they are driven

Figure 3.6
Comparison of Removal Rates Attributed to Volatilization and Biodegradation During Soil Venting at the Tyndall AFB Site



Source: Miller 1990

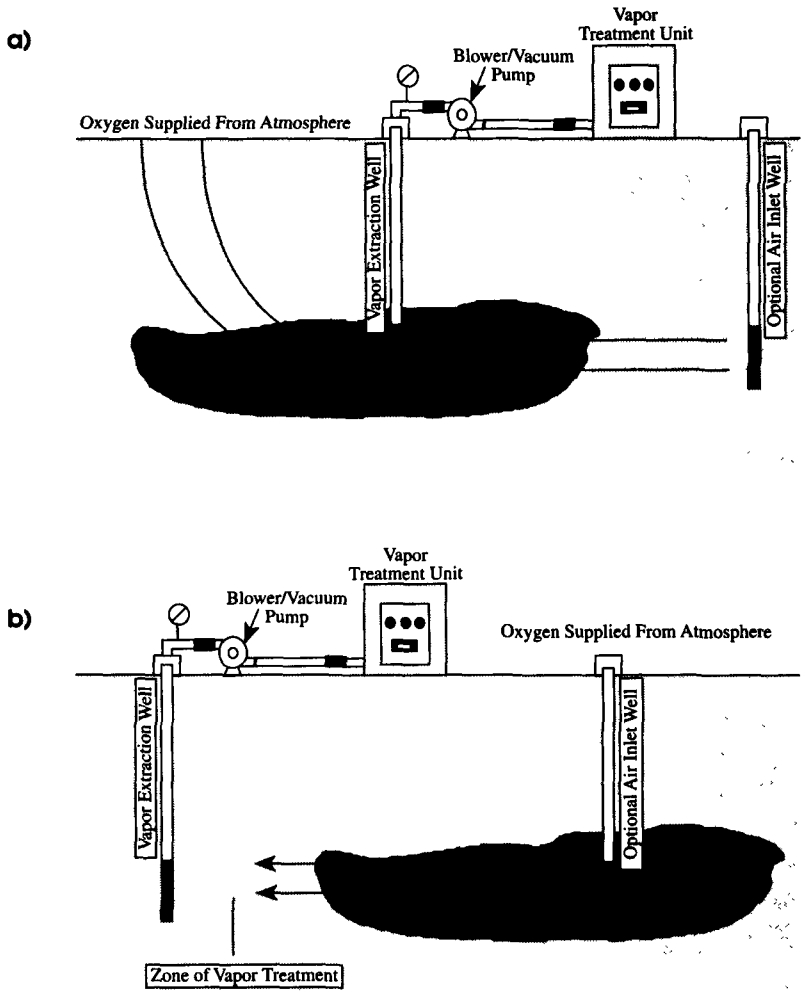
away from that zone. This design is not discussed at length in this document as it is neither an extraction nor a vapor-extraction based technology.

Bioventing clearly represents a positive advance in vapor extraction-based applications at sites having aerobically-degradable contaminants in the unsaturated zone. This technology extends the potential application of soil vapor extraction to sites contaminated with semivolatile fuel hydrocarbons, while requiring minimal modification of soil vapor extraction system design.

3.1.4 Thermal Enhancements of Soil Vapor Extraction

It is generally accepted that soil vapor extraction becomes less practicable for compounds with vapor pressures less than 0.1 mm Hg to 1.0 mm Hg at ambient temperatures. It is expected, however, that the range of ap-

Figure 3.7
Simplistic Bioventing Process Schematics



Based on Hinchee et al. 1989

plicability can be extended by heating the subsurface, as contaminant vapor pressures increase with temperature (assuming that removal rates are roughly proportional to the partial pressure of a compound).

In addition, it is expected that microbiological activity can be increased by gently warming the subsurface to temperatures in the range of 30° to 40°C (86° to 104°F), as biodegradation rates are expected to double for every 10°C (50°F) temperature increase when other factors are not limiting. Temperatures above this range are likely to be inhibitive.

There are a number of alternative in situ heating methods currently being studied, including steam injection, hot-air injection, electrical-resistance heating, radio-frequency heating, thermal-conduction heating, warm water injection, and solar heating. While heated air injection is probably the most practicable if obvious safety concerns are addressed (see Subsection 3.1.2), it is not a very efficient means for delivering heat to the subsurface, given the relatively low-heat capacity of air. For this reason, the alternate energy delivery systems listed above are being investigated.

Few reports concerning in situ heating methods have been published and they are considered to be developmental. But, surveys of thermally-enhanced vapor extraction processes can be made by reviewing journal and conference articles and the patent literature. For example, Bridges et al. (U.S. 4,376,598) and Johnson et al. (U.S. 5,076,727) disclose processes for radio-frequency heating, Nelson and Rau (U.S. 5,011,329) describe a hot-gas injection system, and Johnson et al. (U.S. 5,114,497) describe a thermal conduction scheme for the treatment of contaminated surficial soils. See Section 3.7 for a more complete description of in situ heating methods.

3.2 Fundamentals and Basic Phenomena

The performance of vapor extraction-based processes can be related to three primary factors: equilibrium partitioning into the vapor space in a porous medium, vapor-flow characteristics in the porous medium, and mass-transfer considerations and limitations. In the subsections immediately following, the subsurface distribution of contaminants is described qualitatively and a mathematical framework for discussing each of the factors identified above is established. It will be seen that the ability to quan-

tify these phenomena plays an important role in the design of pilot-scale tests, evaluation of the data, and design of remedial systems.

3.2.1 Qualitative Description of the Subsurface Distribution of an Immiscible Liquid

Typically, sites that are considered candidates for soil vapor extraction and other vapor extraction-based technologies are locations where petroleum products (e.g., gasoline and other fuels) or chlorinated solvents have spilled or leaked into the subsurface. These materials are often called "immiscible liquids," because of their limited solubility in water at environmental pressures and temperatures. In typically released quantities of the spilled liquids, they do not dissolve completely in the soil moisture or groundwater and, consequently, a separate nonaqueous (not dissolved in water) liquid phase is introduced into the subsurface. Immiscible liquids may be chemically homogeneous, that is, they may consist predominantly of one molecular constituent, as in a spill of a solvent comprised almost entirely of trichloroethylene (TCE). The immiscible liquid in spilled refined petroleum products, however, is typically chemically heterogeneous, being a mixture of molecular constituents. For example, gasoline is a mixture of hundreds of hydrocarbon constituents.

Immiscible liquids are called "light nonaqueous phase liquids" (LNAPLs) if their density is less than that of water, or DNAPLs if their density is greater than that of water. For example, gasoline (density $\approx$0.8 g/cm^3 (50 lb/ft^3)) is an LNAPL and TCE (density $\approx$1.5 g/cm^3 (95 lb/ft^3)) is a DNAPL. When a release of either occurs, the liquid is driven downward by gravity. In the course of its migration, lateral spreading of the liquid occurs because of variations in soil permeability and layering, and liquid is retained in the soil pores because of capillary forces. The amount of immiscible liquid immobilized in this way per unit of contaminated sediment is referred to as the "residual saturation" in the soil matrix. For example, Hoag and Marley (1986) determined residual saturations of gasoline to be 26,000 and 44,000 mg gasoline/kg soil for a medium and fine sand, respectively. In small releases, all the liquid eventually becomes trapped and is immobile; however, in more extensive spills, the capacity of the soil to immobilize the liquid is exceeded and immiscible liquid drains to the water table. At this point, LNAPLs spread laterally across the capillary fringe, while DNAPLs continue to migrate below the water table until they become immobilized or encounter a confining soil layer. Although the water table

provides an initial physical barrier for LNAPLs, a significant volume of LNAPLs is often found trapped in a "smear zone" beneath the water table because of natural water table fluctuations and remedial activities (e.g., pump-and-treat operations). This resulting distribution of immiscible liquid in and near groundwater controls the rate at which constituents solubilize and enter underlying groundwater, as well as the rate at which constituents can be removed by vapor extraction. Essaid, Herkelrath, and Hess (1991) provide a detailed description of the distribution of air, oil, and water adjacent to the water table at a U.S. Geological Survey research site near Bemidji, Minnesota.

Layered lithologic units complicate the conceptualization of immiscible contaminant migration outlined above. For example, a lens of clay or fine silty sand can provide a physical barrier between the contaminant source and the water table, thereby causing the immiscible liquid to "pond" on top of the less permeable unit. As will be seen, heterogeneities in lithology also affect the distribution of air flow in the unsaturated zone for a given vapor extraction installation. Therefore, identification and characterization of subsurface heterogeneities is essential for the designing of vapor extraction systems.

Although physical properties of the liquid (e.g., density and surface tension) and the subsurface media control the initial migration and distribution of immiscible liquids, the partitioning of constituents of these liquids into aqueous, gaseous, and sorbed phases is also significant. The partitioning of constituents into the aqueous phase affects water quality problems resulting from a release, while partitioning into the vapor phase is a controlling factor for vapor extraction-based technologies (one of the goals is to remove the vapors efficiently). Although trapped immiscible liquids are said to be immobile, constituents of these liquids continue to migrate in the environment as a result of partitioning. Constituents that dissolve in the soil moisture are predominantly transported by leaching and groundwater movement, while those partitioned into the vapor phase migrate as a result of vapor-phase diffusion or induced vapor flow (as in the application of vapor extraction-based technologies). Historically, aromatic hydrocarbons (e.g., benzene, toluene, and xylenes) have been of primary concern in petroleum product spills, since they are the most soluble constituents (see Subsection 3.2.3) and benzene is a known human carcinogen (US EPA IRIS Database 1993). Fortunately, these compounds also partition significantly into the vapor phase and are often effectively removed by vapor extraction-based

technologies (see figure 3.8 on page 3.20; see also figure 3.9 on page 3.21). Total volatile hydrocarbons consist of the sum of volatilized constituents of the petroleum product that have migrated away from the oil body.

The microbial degradation of contaminants provides another mechanism for the attenuation of compounds present in the unsaturated zone. In aerobic degradation, bacteria use oxygen to break down contaminants into carbon dioxide, water, and biomass (cells). Microbial degradation rates, however, are often limited by the diffusive recharge of oxygen from the atmosphere into the contaminated zone under natural conditions. Thus, another beneficial consequence of vapor extraction is that of greatly enhancing the rate at which oxygen is recharged, often resulting in increased microbial degradation rates. This is the basis for bioventing. See figures 3.10a and 3.10b (page 3.22); at this site, the microbial degradation rate in the most highly-contaminated zone surrounding the former location of the leaking tank is limited by the rate of oxygen diffusion.

3.2.2 Quantitative Description of Multiphase Partitioning

The extent and rate of the partitioning among vapor, aqueous (soil moisture), sorbed, and immiscible (residual liquid or solid) phases in the subsurface described in Subsection 3.2.1, above, play a significant role in contaminant migration and, consequently, influences the performance of any vapor extraction-based process. Thus, it is important to quantify this phenomena. In this section the working approximation used by Corapcioglu and Baehr (1987), Johnson, Kemblowski, and Colthart (1988), and Johnson et al. (1990) is followed in order to establish a framework for mathematically describing the chemical partitioning within soil matrices. The goal is to develop a model that can be used to predict equilibrium vapor concentrations of compounds in the subsurface. The use of this information in estimating the performance of vapor extraction-based processes will be demonstrated in subsequent sections.

In general, the total volumetric concentration T_j (g-j/cm^3-soil) of component j can be distributed in the subsurface between vapor, aqueous (soil moisture), sorbed, and immiscible phases as described by the mass balance:

$$T_j = \theta_a G_j + \theta_w C_j + \rho_b S_j + \theta_i I_j \qquad [3.1]$$

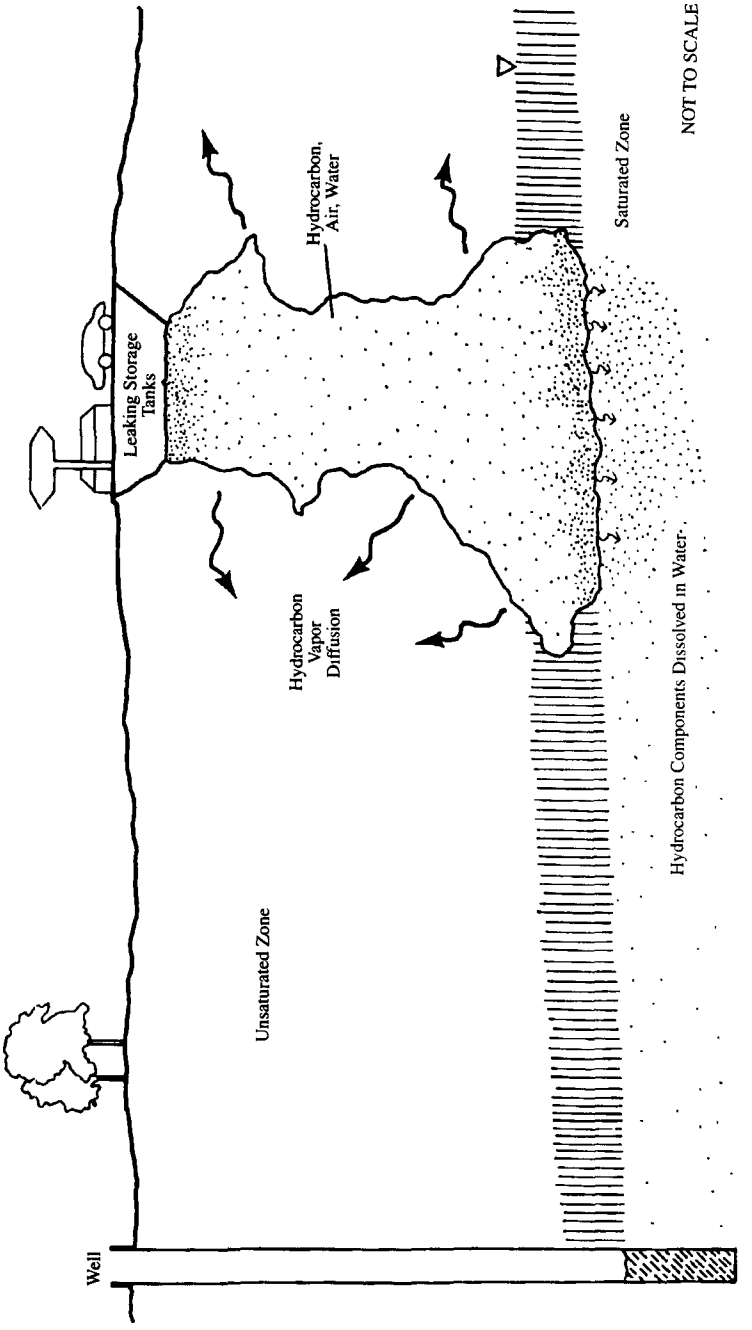
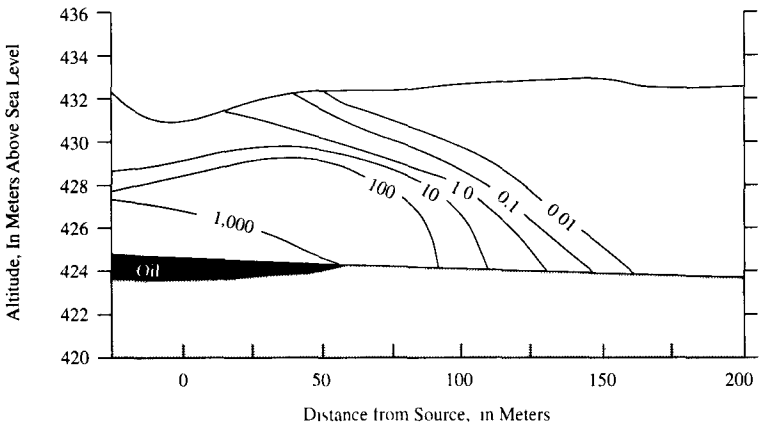


Figure 3.8
Illustration of Multi-Phase Hydrocarbon Distribution Resulting from an Underground Gasoline Storage Tank Leak

Figure 3.9
Cross Section Illustration of Concentration of Total Volatile Hydrocarbons Detected in Soil Gas at USGS Study Site Near Bemidji, MN



——10—— Total Volatile Hydrocarbons, in grams per cubic meter

Source Hult, Landon, and Pfannkuch 1991

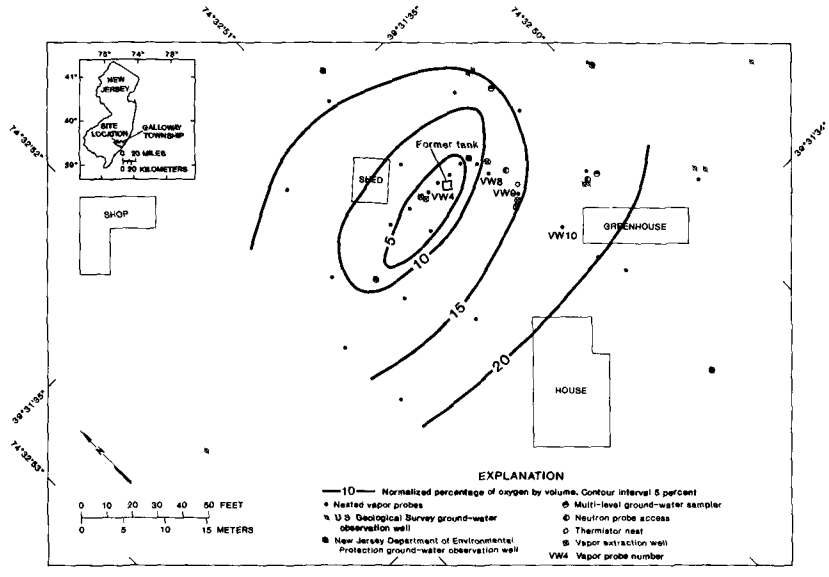
where θ_a, θ_w, and θ_i denote the volumetric contents (cm^3/cm^3-soil) of the vapor, aqueous, and immiscible phases, respectively, and ρ_b is the soil bulk density (g-soil/cm^3-soil). The volumetric concentrations of component j in the vapor, aqueous, and immiscible phases are denoted G_j, C_j, and I_j (g-j/cm^3-vapor, -water, or -immiscible phase), respectively. The symbol S_j represents the amount of component j that is sorbed to the solid matrix per unit mass of soil (g-j/g-soil). For equation [3.1] to be useful, supplemental relations describing the equilibrium between phases must be supplied. The idealized relationships that are standardly applied in this analysis are examined next.

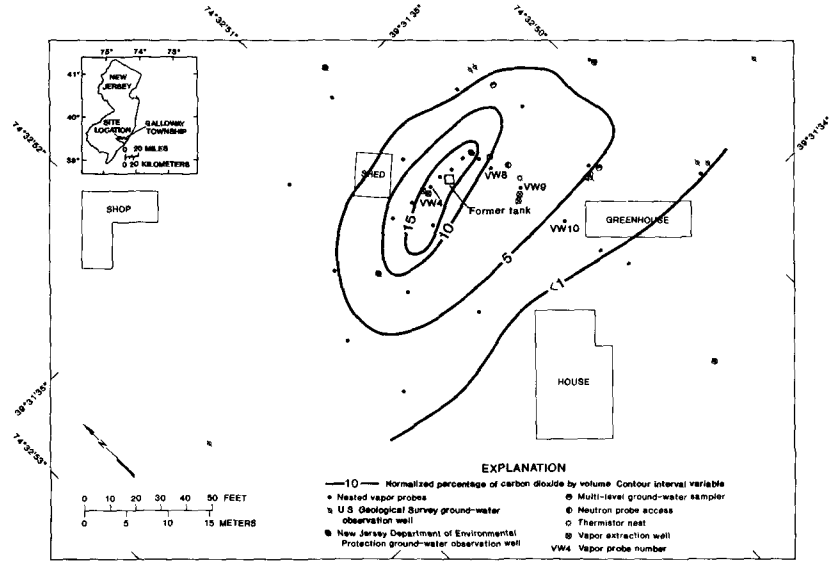
Raoult's Law (Atkins 1978) is assumed to quantify the equilibrium between immiscible and gaseous phases; the gaseous phase concentration G_j (g-j/cm^3-vapor) of constituent j is related to the mole fraction χ_j (dimensionless) of constituent j in the immiscible phase and the saturated vapor concentration G_j^{sat} (g-j/cm^3-vapor):

$$G_j = \chi_j \; G_j^{sat} \qquad [3.2]$$

Figure 3.10

Areal Distribution of (a) Oxygen and (b) Carbon Dioxide as a Percentage of the Soil Gas at a Depth of 6 ft BGS at the Galloway Township, NJ, Gasoline-Spill Site, December 1989





Source: Baehr and Hult 1991

Here G_j^{sat} is defined:

$$G_j^{sat} = \frac{M_{w,j} P_j^v}{RT} \qquad [3.3]$$

where $M_{w,j}$ (g-j/mole) is the molecular weight of the jth constituent, R is the gas constant (82 cm^3-atm/mole-K), T is the absolute temperature (K) and P_j^v is the vapor pressure (atm) over the pure constituent j at temperature T. For most compounds, P_j^v can be found in standard reference books (e.g., Verschueren 1983) for typical ambient temperatures (i.e., 20° to 25°C (68° to 77°F)). To extrapolate to other temperatures, the Clausius-Clapeyron equation (Atkins 1978) for liquid-vapor equilibrium is often used:

$$P_j^v = \exp\left[- \frac{\Delta H_{v,j}}{RT} + B_j \right] \qquad [3.4]$$

where $\Delta H_{v,j}$ is the molar heat of vaporization (cal/mole), R is the gas constant (1.99 cal/mole-K) and B_j is a unitless constant. Values for $\Delta H_{v,j}$ can be found in standard thermodynamic tables (e.g., Weast 1970), then B_j can be determined by solving equation [3.4] for B_j at a known temperature and reference vapor pressure.

The equilibrium between aqueous and immiscible phases is assumed to be described by an expression analogous to equation [3.2]:

$$C_j = \chi_j C_j^{sat} \qquad [3.5]$$

where C_j (g-j/cm^3-H_2O) is the concentration of the jth constituent in the aqueous phase and C_j^{sat} (g-j/cm^3-H_2O) is the solubility of the pure constituent j in water.

Henry's Law defines the equilibrium between aqueous and gaseous phases as follows:

$$G_j = H_j C_j \qquad [3.6]$$

where H_j is the Henry's Law partition coefficient. To maintain consistency with equations [3.2], [3.5], and [3.6], H_j is defined as follows:

$$H_j = \frac{G_j^{sat}}{C_j^{sat}} \qquad [3.7]$$

Equation [3.7] also applies to regions of the unsaturated zone where the immiscible phase is not present.

The mass of constituent j adsorbed to solid surfaces per unit mass of subsurface soil, S_j, is often described as a function of the aqueous phase concentration and a sorption coefficient $k_{s,j}$. The simplest expression of this relationship is a linear isotherm:

$$S_j = k_{s,j} C_j \qquad [3.8]$$

The sorption coefficient is generally taken to be a function of the fraction of organic carbon f_{oc} in the solid matrix (except for very low f_{oc}) and is determined experimentally or estimated from one of several published correlations (Lyman, Reehl, and Rosenblatt 1982). One expression that is commonly used for gasoline-range compounds is the Karickhoff (1981) equation:

$$k_{s,j} = 0.63 k_{ow,j} f_{oc} \qquad [3.9]$$

where $k_{ow,j}$ denotes the octanol-water coefficient for compound j.

See table 3.1 (on page 3.25) for values of G_j^{sat}, S_j, H_j, and $k_{ow,j}$ for selected hydrocarbons. The reader can consult sources cited in the table for values for other compounds.

Equilibrium expressions [3.1] through [3.9], subject to the constraint:

$$\sum_{j=1}^{n} \chi_j = 1 \quad \text{n} = \text{\# of components} \qquad [3.10]$$

provide a working approximation for equilibrium partitioning in porous media. In general, solution of this set of equations is cumbersome and requires iteration; however, useful approximations result when the limits of "high" and "low" total volumetric concentrations are evaluated. Figure 3.11 (on page 3.26) presents the results of model calculations for gasoline in

Table 3.1
Thermodynamic Data for Selected Hydrocarbons (T = 20°C)

	G_j^{sat} [g/cm³-vapor x 10³]	C_j^{sat} [g/cm³-H_2O x 10³]	H_j [cm³-H_2O/cm³-air]	$K_{ow,j}$ [cm³-H_2O/g-soil]
benzene	0.303	1.78	0.17	135
n-hexane	0 617	0 0095	64.9	8710
toluene	0 133	0.515	0.26	490
o-xylene	0 037	0.175	0 21	589

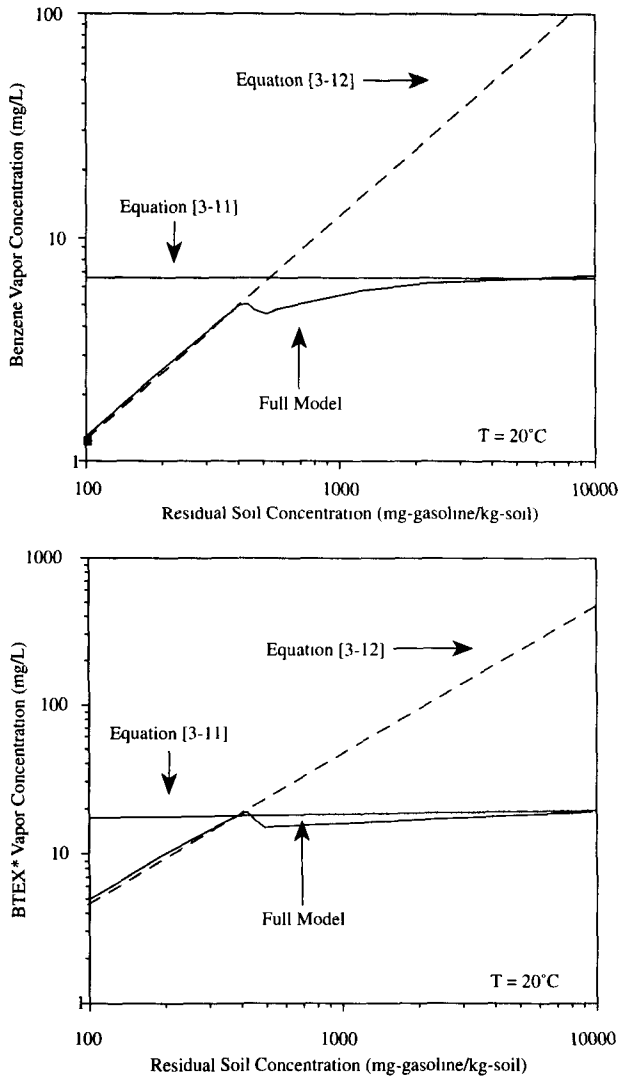
G_j^{sat} calculated from Equation [3 3] and values from Weast 1970
C_j^{sat} from Verschueren 1983
Another source of basic data MacKay and Shiu 1981

a sandy soil. In this figure, the "full" model refers to solutions of equations [3.1] through [3.10]. In the limit of high concentrations (>500 mg-gasoline/kg-soil), the vapor concentrations become independent of the total gasoline concentration and depend only on composition (the inflection point in figure 3.11 (on page 3.26) is an artifact of the calculation procedure and is not expected to be a "real" phenomenon). Thus, the vapor-phase concentration is adequately predicted by equations [3.2] and [3.3], rewritten here as:

$$G_j = \chi_j \frac{P_j^v M_{w,j}}{RT} \qquad [3.11]$$

As illustrated by figure 3.11 (on page 3.26), the maximum vapor concentration achievable in the porous medium is that value predicted by equation [3.11]. At most sites, equation [3.11] is likely to provide a reasonable estimate of vapor concentrations and partitioning corresponding to conditions before remediation. To estimate this upper bound, one needs to know only two chemical-specific properties (P_j^v and $M_{w,j}$), as well as an approximation of the spilled product (immiscible phase) composition (χ_j). For refined hydrocarbon mixtures, such as gasoline, hundreds of compounds can be identified; thus, it is often necessary to approximately define the composition by grouping compounds into constituent classes, as illustrated for gaso-

Figure 3.11
Comparison of Vapor Concentration Prediction Models



* denotes the sum of benzene, toluene, ethylbenzene, and xylenes vapor concentrations

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line in table 3.2. Another example of grouping compounds can be found in table 2 of Johnson et al. (1990). Note that a single hydrocarbon can define a class (e.g., benzene) if the hydrocarbon partitioning properties in the mixture are representative of the range of interest. The approximate composition given in table 3.2 was based on the packed-column gas chromatograph analysis of a regular, leaded gasoline reported by Bruell and Hoag (1984). A constituent class is assigned properties by identifying a composite chromatographic peak with a known standard. Note that for this gasoline, the aromatic constituents, benzene, toluene, and three xylene isomers, made up 20.1% of the product, but account for about 80.6% of the total volatile hydrocarbons partitioned in the aqueous phase, because nonaromatic hydrocarbons have very low solubilities. Note also that the gaseous phase partition (the portion available for venting) is significant for all classes of

Table 3.2
Gasoline Hydrocarbons Grouped in Constituent Classes

		$M_{w,J}$ g/mole	x_J unitless	G_J^{sat} g/cm³ x 10³	C_J^{sat} g/cm³ x 10³
1	benzene	78	0.044	0.303	1.78
2.	toluene	92	0.064	0.134	0.515
3.	C_8 aromatics	106	0.093	0.044	0.156
4.	C_9-C_{11} aromatics	132	0.173	0.014	0.040
5.	C_5 alkenes	70	0.073	1.69	0.203
6.	C_5-C_6 alkenes	83	0.252	0.70	0.021
7.	C_6 napthenes	84	0.035	0.55	0.055
8.	C_7-C_{11} alkanes	113	0.241	0.25	0.002
9.	C_6-C_{11} alkenes	103	0.017	0.13	0.030
10	C_7-C_{11} napthenes	98	0.008	0.12	0.030

G_j^{sat} - Saturated vapor concentration
C_J^{sat} - Saturated dissolved concentration - solubility
Source: Corapcioglu and Baehr 1987

hydrocarbons. Another method of identifying classes of constituents, based on the boiling points of known standards and their retention time for a selected chromatographic method, is discussed by Johnson et al. (1990).

In the limit of low hydrocarbon concentrations, the equilibrium partitioning model reduces to:

$$G_j = \frac{H_j T_j}{\left[H_j \theta_a + \theta_w + \rho_b k_{s,j}\right]} \qquad [3.12]$$

which predicts that the equilibrium vapor concentration is proportional to the residual concentration of j in the subsurface and is independent of composition as exhibited by the results presented in figure 3.11 (on page 3.26). This low concentration regime is sometimes referred to as the "Henry's Law Limit", and its effect may be significant near the completion of remediation by soil venting or where there are very highly water soluble compounds, such as oxygenated hydrocarbons. Equation [3.12] indicates that venting is inherently less efficient as the process progresses because the vapor concentration of compound j decreases in proportion to decreases in the concentration of j in the subsurface. This has serious practical implications at sites where the goal is to achieve extremely low levels (ppb range) of residual contamination.

3.2.3 Basis for Mathematical Models of Induced Air Flow in the Unsaturated Zone

The success of a vapor extraction installation is fundamentally dependent upon the establishment of an air-flow field that intersects the contaminant in the unsaturated zone. The air-flow field developed for a given configuration of extraction and injection wells depends on many factors, including the pump(s) employed, screened intervals of the wells, depth to groundwater, and the spatial distribution of air permeability in the unsaturated zone. A mathematical model of induced airflow in the unsaturated zone provides a valuable tool for simultaneously considering the effect of these factors. The following discussion outlines the derivation of the general model presented in detail by Baehr and Hult (1991) and then presents solutions for a number of simplified scenarios.

Some readers will note similarities between the mathematical framework given below and that commonly used when developing mathematical models of groundwater flow phenomena. The main physical difference between the two being that vapors are compressible under most practical situations, while groundwater is not. If compressibility is neglected, vapor and groundwater flow equations are identical, and all of the analytical and numerical tools developed for groundwater applications are directly applicable, upon substitution of the appropriate fluid properties (Massman 1989). Even when compressibility is retained in the development (as is done here), the groundwater flow-vapor flow similarity is retained in many cases. For example, it well be seen in Section 3.2.6 that equations governing the pressure (head) field are similar in form as long as the vapor pressure field equation is expressed in terms of the square of the pressure. To date, this similarity has not been fully exploited in the development of predictive tools for vapor flow.

The equation governing airflow in an unsaturated, porous medium originates with a mathematical expression of mass conservation:

$$\frac{\partial(\rho_a \theta_a)}{\partial t} + \underline{\nabla} \bullet \left(\rho_a \underline{q}_a\right) = 0 \qquad [3.13]$$

where ρ_a (g/cm^3) is the density of the vapor phase, θ_a (cm^3-vapor/cm^3-soil) is the vapor-filled porosity, and t(s) is the time. The specific discharge (darcy velocity) vector q_a (cm/s) is assumed to be related to the fluid potential Φ (cm^2/s^2) through the following form of Darcy's Law:

$$\underline{q_a} = -\frac{\rho_a}{\mu} \underline{\underline{k}} \bullet \underline{\nabla}\Phi \qquad [3.14]$$

where μ (g/cm-s) and $\underline{k}$ (cm^2) denote the vapor phase viscosity and air permeability tensor, respectively. For compressible fluids (i.e., gases), Φ is given by (Hubbert 1940):

$$\Phi = gz + \int_{P_o}^{P} \frac{dP}{\rho_a} \qquad [3.15]$$

where z (cm) represents the elevation, P (g/cm-s^2) is the vapor phase pressure, and P_o (g/cm-s^2) is a reference vapor phase pressure. To complete the mathematical formulation, a constitutive expression relating vapor-phase density ρ_a and pressure P is needed. Here, the Ideal Gas Law is adopted:

$$\rho_a = \frac{M_w P}{R\ T} \qquad [3.16]$$

where M_w (g/mole) is the average molecular weight of the vapor phase, R is the universal gas constant (82.1 cm^3-atm/mole-K), and T (K) is the absolute temperature.

By first substituting equation [3.16] into equation [3.15] and then assuming that M_w is constant and the first term on the right side of equation [3.15] is negligible in comparison to the second term (a good assumption for flows induced by pressure gradients), a simplified expression for the fluid potential can be derived. When this expression is inserted into equation [3.14], Darcy's Law reduces to:

$$\underline{q_a} = \frac{-1}{\mu}\underline{\underline{k}} \bullet \underline{\nabla} P \qquad [3.17]$$

Equations [3.16] and [3.17] can be inserted into the mass balance equation [3.13] to obtain the governing equation for airflow:

$$(2\theta_a \mu)\frac{\partial P}{\partial t} = \underline{\nabla} \bullet \underline{\underline{k}} \bullet \underline{\nabla} P^2 \qquad [3.18]$$

Analytical solutions to equation [3.18] for a number of simplified scenarios are presented in Subsection 3.2.4, below. These are useful in identifying parameters that affect air-flow behavior, as well as in estimating ranges of possible behavior that might be observed in the field.

3.2.4 One-Dimensional Vapor Flow Scenarios

Figure 3.12 (on page 3.32) depicts two one-dimensional flow scenarios. Figure 3.12a shows the flow between two semi-infinite flat plates; figure 3.12b shows one-dimensional radial flow. The former is a first order ap-

proximation of flow to a trench or flow in a laboratory soil column and the latter is often used as an approximation of flow to a vertical well. If a homogeneous media with constant air permeability and steady-state flow is assumed, then equation [3.18] reduces to:

$$0 = \frac{\partial P^2}{\partial x} \qquad \text{(linear flow) [3.19a]}$$

$$0 = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P^2}{\partial r}\right) \qquad \text{(radial flow) [3.19b]}$$

In each case boundary conditions must be specified at two locations; typically these take the following form:

$$P = P_w \quad x = 0; \quad P = P_{atm} \quad x = L_{atm} \qquad \text{(linear flow) [3.20a]}$$

$$P = P_w \quad r = R_w; \quad P = P_{atm} \quad r = R_{atm} \qquad \text{(radial flow) [3.20b]}$$

where P_{atm} denotes atmospheric pressure and P_w is the pressure applied at the vapor extraction location. It is important to note that pressures given here are absolute pressures and not the gauge pressures ($P_g = (P - P_{atm})$) typically measured in the field. The solutions for the pressure distribution and flow rates at the extraction locations for each scenario are:

$$P^2 = \left[\frac{\left(P_{atm}^2 - P_w^2\right)}{L_{atm}}\right] x + P_w^2 \qquad \text{(linear flow) [3.21a]}$$

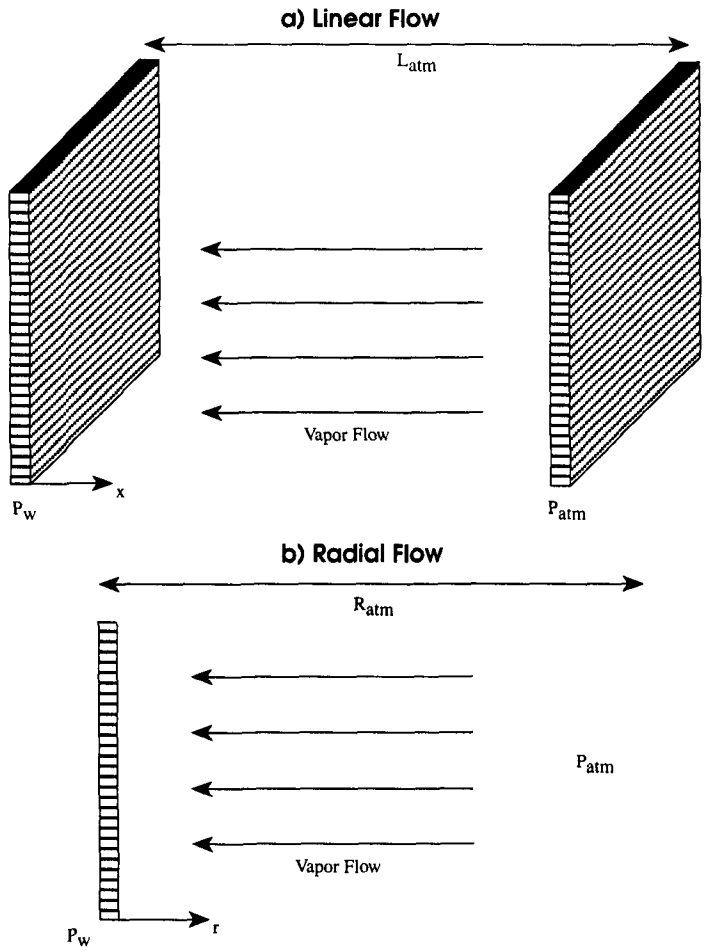
$$P^2 = P_w^2 + \left(P_{atm}^2 - P_w^2\right)\frac{\ln\left(r / R_w\right)}{\ln\left(R_{atm} / R_w\right)} \qquad \text{(radial flow) [3.21b]}$$

The corresponding relationships between volumetric extraction rates Q (cm^3/s) and applied vacuums P_w ($g/cm\text{-}s^2$) are:

$$Q = 2q_a(x=0)HW = HW\left(\frac{k}{\mu}\right)\frac{\left[P_{atm}^2 - P_w^2\right]}{L_{atm}P_w}$$

(linear flow) [3.22a]

Figure 3.12
One-dimensional Vapor Flow Scenarios

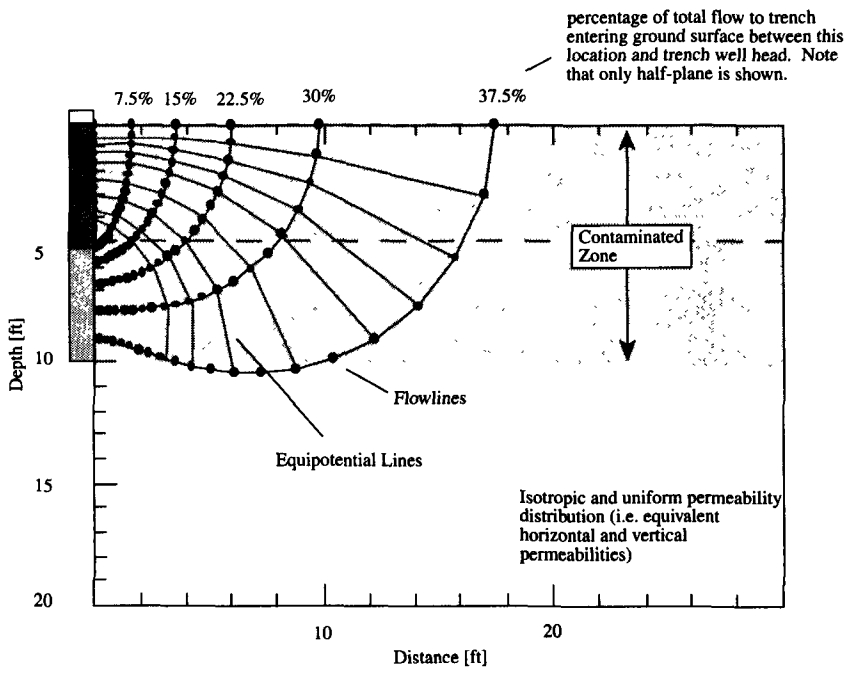


$$Q = 2\pi\ q_a(r = R_w) = H\left(\frac{\pi k}{\mu}\right) P_w \frac{\left[1 - (P_{atm} / P_w)^2\right]}{\ln(R_w / R_{atm})}$$

(radial flow) [3.22b]

Here the convention that flow rates are positive if a vacuum is applied at the designated extraction location (i.e., x = 0 and r = R_w) is used. The thickness of the permeable zone in both cases is designated H, and W represents the width of the extraction location in the linear flow case (HW is then the cross-sectional extraction flow area).

Figure 3.13
Predicted Vapor Flowlines to a Vapor Extraction Trench



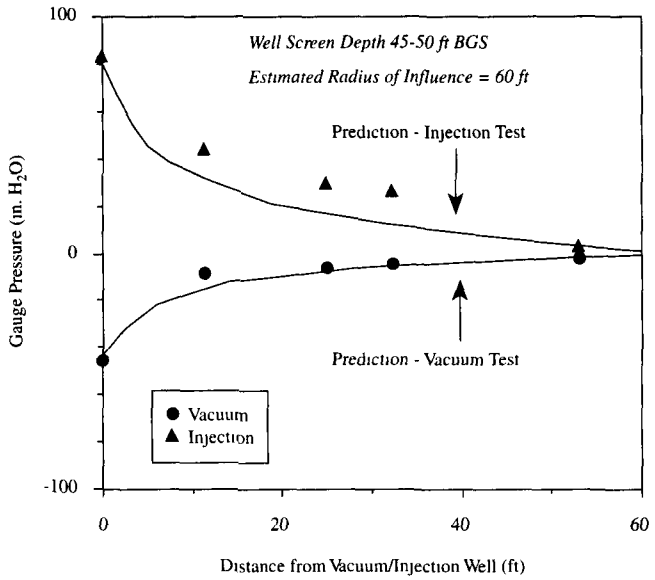
Source: Johnson and Ettinger 1992

If applying a one-dimensional solution given by either equation [3.21] or [3.22], one must fully understand the nature of the geometric approximation; otherwise, false conclusions can result from the analysis. For example, in the case of a single extraction well, the source of air to the well is the atmosphere and therefore all flow paths intersect the land surface. Figure 3.13 illustrates the predicted two-dimensional flow paths induced by an extraction trench in homogeneous porous media. The solution given by equation [3.21b] is to be interpreted as an approximate pressure distribution with r representing distance along the upwardly curving flow path that intersects the atmosphere at a distance R_{atm} where the pressure is atmospheric P_{atm}. Obviously, a flow path originating near the top of the well screen intersects the land surface at a distance shorter than one originating near the bottom of the well screen. Therefore, the "radius of influence", R_{atm}, predicted in applying the one-dimensional solution here represents some sort of average over all flow paths. Clearly, higher dimensional solutions are required to rigorously analyze flow induced by wells. Use of a higher dimensional model that includes the depth component, z, will result in a more realistic definition of the zone of significant vapor flow.

It is worthwhile noting at this point that equations derived from analyses of simplistic scenarios are misused quite frequently in practice. For example, equations [3.21b] and [3.22b] contain the parameter, R_{atm}, which is a quantity that arises as a consequence of the one-dimensional analysis. But it is necessary to specify that atmospheric pressure is maintained some finite distance from the well, and this distance is referred to as the "radius of influence". A useful feature of equations [3.21b] and [3.22b] is that well flowrate predictions are not especially sensitive to changes in this distance over a reasonable range of values (15 to 60 m (50 to 200 ft)). However, some practitioners have inappropriately associated R_{atm} with a measure of the remedial effectiveness of a vertical extraction well. Consequently, equations [3.21b] and [3.22b] are often improperly used to empirically determine some measure of remedial effectiveness from pilot-test data.

Despite their limitations, the simplistic one-dimensional solutions are useful in identifying parameters that affect air-flow behavior as well as in estimating ranges of possible behavior that might be observed in the field. For example, the one-dimensional radial flow solutions give a useful first-order approximation of behavior that is typically seen in the field with vertical well systems. The characteristic shape of the spatial pressure distribution shown in figure 3.14 (on page 3.35) indicates that measured subsurface vacuums are likely to decrease rapidly within short distances of

Figure 3.14
Predicted and Measured Steady-State Radial Pressure Distributions



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the extraction well. From this, one can deduce that subsurface soil gas pressure monitoring probes should be installed relatively close to extraction/injection wells, if a significant reading is expected. In addition, as the volumetric flow rate is predicted to increase roughly in proportion to the applied vacuum (for low to moderate vacuums) and the soil permeability, then estimates of the subsurface permeability at a site can be used with equation [3.22b] to approximate flow rates that might be achieved in a field-pilot test (see figure 3.15 on page 3.37). In this figure, Q^* (standard ft^3/min) denotes volumetric flow rates normalized to atmospheric pressure (i.e.,

$$Q^* = Q(P = P_w)\left(\frac{P_w}{1atm}\right)).$$

3.2.5 Two-Dimensional Vapor Flow Scenarios

Two-dimensional analyses result from the retention of an added spatial dimension or time. For a homogeneous porous media and transient radial flow, the approximate solution (for $P^2 \approx PP_{atm}$) to equation [3.18] is (Johnson et al. 1990):

$$P_{atm} - P_w = \frac{Q}{4\pi H(k/\mu)} \int_{\frac{r^2\theta_a\mu}{4kP_{atm}t}}^{\infty} \frac{e^{-x}}{x} dx \qquad [3.23]$$

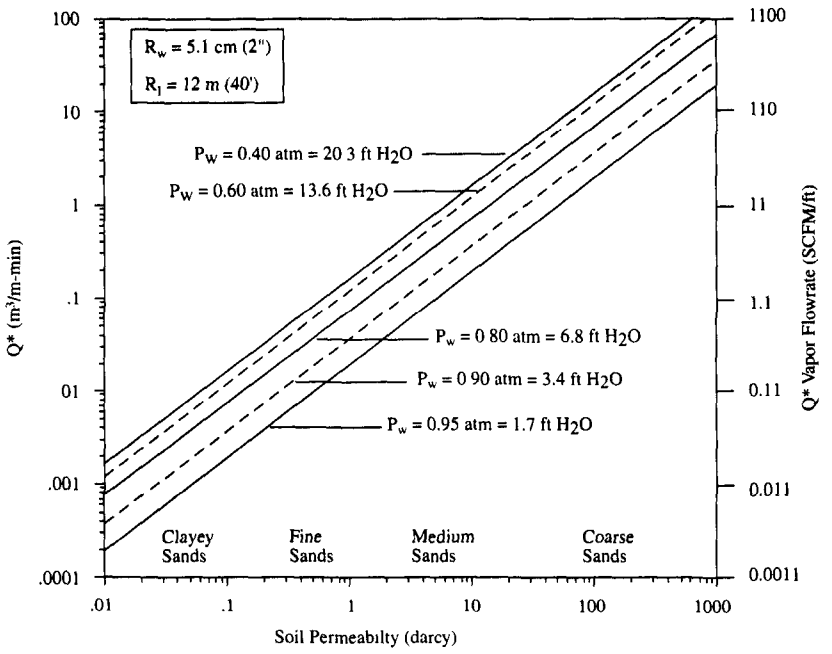
where all parameters are defined above. If $(\frac{r^2\theta_a\mu}{4kP_{atm}t})<0.1$, then equation [3.23] can be linearized to the form:

$$P_{atm} - P_w = \frac{Q}{4\pi H(k/\mu)} \left[-0.5772 - \ln\left(\frac{r^2\theta_a\mu}{4kP_{atm}t}\right)\right] \qquad [3.24]$$

Equations [3.23] and [3.24] can be used to estimate the time to establish steady flow or to estimate the integrated subsurface air permeability from transient field subsurface pressure measurements. Equation 3.24 actually predicts that steady-state is never truly reached, so it is necessary to look at the time it takes to achieve some percentage of the long-term value. For relatively permeable soil types (e.g., sands and gravels) it is predicted that steady-state flow conditions are achieved in a matter of minutes. Steady conditions will take longer to establish in clayey soils; however, typical transient responses reach steady conditions in a matter of minutes or hours. This valuable information allows one to focus on predicting steady flow fields when using more sophisticated flow models. It should be noted that the time to reach steady conditions also increases with distance from the extraction well.

Other two-dimensional solutions are found by adding the depth dimension, z, in the polar coordinate system. This allows development of a more representative steady-flow model. Assuming that the unsaturated zone is homogeneous and anisotropic with respect to air-phase permeability (i.e., vertical and horizontal components of air permeability are defined and are constant over the domain), the air-flow equation [3.18] for the axisymmetric (single well) two-dimensional polar coordinate system reduces to:

Figure 3.15
Predicted Steady-State Flow Rates (Per Unit Well Screen Depth) for a Range of Soil Permeabilities and Applied Vacuums (Pw)



[ft H_2O] denote vacuums expressed as equivalent water column heights

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$$k_r \frac{\partial^2 P^2}{\partial r^2} + \frac{k_r}{r} \frac{\partial P^2}{\partial r} + k_z \frac{\partial^2 P^2}{\partial z^2} = 0 \qquad [3.25]$$

where, r and z are polar coordinates aligned along the major axes of the air permeability tensor with radial and vertical components k_r and k_z (cm^2).

A computer code recently developed by Joss and Baehr (1993a), which is in the public domain, implements solutions to equation [3.25] subject to various characterizations of the land surface boundary condition. This code

is an adaptation of the groundwater flow code: MODFLOW. The solutions are derived according to the method presented by Baehr and Hult (1991). Code output includes air pressure and flow vectors in the simulated domain surrounding a single injection or extraction well. Analytical solutions for two-dimensional flow to an extraction trench are also presented by Johnson and Ettinger (1994), who derived their solutions using conformal mapping procedures, and Shan, Falta, and Javandel (1992). Numerical solutions of two-dimensional flow problems are presented in a series of articles by Wilson and others (Gannon et al. 1989; Gomez-Lahoz, Rodriguez-Maroto, and Wilson 1991; Mutch and Wilson 1990). Flow lines depicted in these articles are useful in developing a practical intuition concerning air-flow dynamics.

3.2.6 General Air-Flow Modeling Considerations

The most general steady-state modeling and design problem is, of course, fully three dimensional. A three-dimensional model allows simultaneous simulation of multiple wells, heterogeneity in air-phase permeability due to unsaturated zone stratigraphy, and variable moisture content, as well as a variety of boundary conditions. The steady-state air-flow equation for a three-dimensional, cartesian coordinate system is as follows:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial^2 P^2}{\partial x^2}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial^2 P^2}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial^2 P^2}{\partial z^2}\right) = 0 \qquad [3.26]$$

where x, y, and z are cartesian coordinates aligned along the major axes of the permeability tensor with components k_{xx}, k_{yy}, and k_{zz}. A computer code developed by Joss and Baehr (1993b), also in the public domain, solves equation [3.26], subject to a variety of boundary conditions that can be encountered at field sites. The code was developed by adapting the U.S. Geological Survey groundwater flow simulator, MODFLOW, when the similarity between the groundwater flow equation and equation [3.26] was recognized. Other computer codes, such as CSUGAS (Sabadell, Eisenbeis, and Sumada 1988), developed at Colorado State University, are also available for similar purposes.

Analogous to the use of a groundwater flow model in quantifying aquifer flow, an air-flow model can be used in a calibrative mode or a predictive mode. When it is used in a calibrative mode, the objective is to estimate the spatial distribution of air permeability in the unsaturated zone. Air permeability depends on location because of two factors: (1) the nature of the lithologic unit (e.g., coarse or medium sand) and (2) the occupation of void space by the aqueous and immiscible phases. An air-flow model can be calibrated against data collected during a pneumatic pump test (typically involving a single well) to obtain air permeability estimates. When used in a predictive mode, the spatial distribution of air permeability is assumed, and a model can be used to predict air pressure and flow over the domain under many proposed well configurations in order to aid in determining an optimal system design. Pressure vs. discharge relationships at extraction wells can be simulated to assist in the selection of pumps. The effect of heterogeneity in air permeability, caused by layers of different lithologic units on the distribution of flow velocity in the domain, can be simulated to estimate cleanup times. A model used in the predictive mode is able to calculate a zone of influence based on flow velocity, rather than on an arbitrary criterion based on measured air pressure.

3.2.7 Transport Considerations and the Estimation of Removal Rates and Residuals

As mentioned previously, the two main factors that govern the performance of vapor extraction-based processes are: (1) chemical partitioning to the vapor phase (see Subsection 3.2.2) and (2) vapor flow behavior (see Subsections 3.2.3 through 3.2.6). In combination, they determine subsurface hydrocarbon transport and consequently, the removal rates obtained with any vapor extraction-based system. Subsections 3.2.7 through 3.2.11 examine different ways to combine the information presented in Subsections 3.2.2 through 3.2.6 in order to estimate the performance of vapor extraction-based processes. In Subsections 3.2.4 through 3.2.6, the general approach is outlined, and varying levels of simplification are discussed.

Upon review of the literature, one finds that many different mathematical formulations have been used to describe the vapor-phase transport of chemicals in porous media. Most models account for convective and diffusive transport in similar ways. The differences, however, primarily result

from assumptions used to describe local chemical equilibria and local mass transfer rates between various chemical phases.

The most mathematically convenient approach is to assume that there are no local mass transfer resistances and that partitioning between various chemical phases can be described in terms of strictly linear equations. In this case, the equations governing chemical transport are identical to those commonly used in groundwater transport modeling, and any of a number of existing groundwater contaminant transport tools can be used to predict the performance of vapor extraction systems.

Unfortunately, chemical partitioning in soils does not always behave as predicted by mathematically-convenient linear models, especially in the concentration range for which vapor extraction technologies are most commonly applied. In the approach described below, a more complete mathematical approximation of chemical partitioning in soil matrices is presented. The assumption of local equilibrium, however, is retained. This assumption is justified since the intent is to develop models that will predict optimal vapor extraction system performance. It is implicit that any real system will perform less effectively.

The degree to which local mass transfer rates limit vapor extraction performance is unknown at this time. The mathematical framework can be easily expanded to account for local resistances through the introduction of a number of mass transfer coefficients. In the absence of data, however, most users will be forced to (arbitrarily) select values for these parameters. Johnson et al. (1989) presented an analysis of vapor-phase equilibrium on the pore scale, and concluded that vapor-phase mass transfer resistances would be negligible for typical subsurface vapor velocities induced by soil vapor extraction. Intraparticle mass transfer resistances have been observed, however, during soil-water partitioning experiments. It is possible that these could play a significant role in limiting vapor extraction performance in the instance of low-contaminant concentrations. In Subsection 3.2.11 macro-scale mass transfer limitations resulting from heterogeneous geology and contaminant distributions, are discussed together with the effect that these have on vapor extraction performance.

Whether or not the user is operating under a system controlled by significant mass transfer resistances impacts the optimal operating strategy that is used. In the absence of mass transfer resistances (macro- or micro-scale), removal rates always increase with increased flow rates. Thus, the system

operates at the maximum flow rate achievable by the system. In this case, systems can be designed based on economic constraints, performance goals (remediation time, cleanup level etc.), and a design parameter that represents the minimum volume of vapor required to achieve the desired degree of remediation. The latter is determined form chemical equilibria models, or laboratory soil column experiments. This approach is outlined in Subsection 3.2.9.

When mass transfer resistances govern system performance, the operating strategy is quite different. The user will find that the removal rate does not always linearly increase with flow rate. In fact, as the flow rate is increased the user will eventually observe minimal changes in removal rate with increasing flow rate. This is generally reflected by decreases in offgas concentrations with increases in extraction flow rate. Thus, the operating strategy will be to find the minimum flow rate that achieves the maximum removal rate.

Over the course of most vapor extraction projects, users will find that both operating strategies need to be used. During the initial phase of operation, most systems perform as if there are no mass transfer limits. Later, mass transfer resistances become more important.

Again, the reader is cautioned that local equilibrium is assumed in the following mathematical development, and it is not implied that mass transfer resistances do not play important roles at some sites. Rather, the intent is to develop screening-level models that will predict optimal vapor extraction system performance. It should be understood that any real system will perform less effectively. Such models are often used to identify sites, or conditions, for which vapor extraction is not likely to be successful.

In the most general sense, prediction of the response in the subsurface to the installation and operation of a vapor extraction-based process requires prediction of the induced air-flow field, local equilibrium partitioning of hydrocarbons, and the rate of hydrocarbon transport through the subsurface. The first two are predicted by equations presented in Subsections 3.2.2 through 3.2.6, and the latter is typically described by the equation:

$$\frac{\partial(T_j)}{\partial t} + \underline{\nabla} \bullet \underline{q_a} G_j = \underline{\nabla} \bullet D_j \underline{\nabla} G_j - \lambda f(T_j) \qquad [3.27]$$

for each chemical component. Here T_j (g-j/cm^3-soil) is the total volumetric content of component j, q_a (cm/s) is the specific discharge (Darcy velocity) vector, G_j (g-k/cm^3-vapor) is the vapor-phase concentration of k, D_j (cm^2/s) is the effective dispersion/diffusion coefficient, and $\lambda f(T_j)$ (g-j/cm^3-soil/s) represents losses due to degradation. Underlying equation [3.27] is the assumption that convection occurs most significantly in the vapor phase and that vapor-phase dispersion is the most significant dispersive mechanism. Solution of a three-dimensional transient version of equation [3.27] would provide the most complete tool for predicting vapor extraction-based system performance; however, a model that combines a multiconstituent equilibrium model with three-dimensional air flow is not currently available in the public domain. Even if such a model were available, it might be too costly because of the data and time it would require for application. As with numerical air-flow models, it may be that detailed numerical transport codes are best used for visualization purposes and developing an understanding of what may occur for a given scenario, rather than general application at all sites.

3.2.8 Nondimensional Solutions - Constant Flow/Constant Vapor Concentration

The simplest of all transport models is a nondimensional model that combines vapor concentration G_j (g-j/cm^3) and flow-rate estimates Q (cm^3/s) to produce first-order removal rate estimates. The removal rate of compound j, R_j (g-j/s), and time to achieve cleanup τ (s) are given by:

$$R_j = QG_j \qquad \text{(nondimensional estimate)} \quad [3.28]$$

$$\tau = \langle T_j \rangle V_{soil} / R_j \qquad \text{(nondimensional estimate)} \quad [3.29]$$

Here, Q and G_j are calculated as explained in Subsections 3.2.2 through 3.2.6, and V_{soil} denotes the volume of soil (cm^3) containing the average total volumetric contaminant concentration $\langle T_j \rangle$ (g/cm^3). While this model neglects a number of significant phenomena and is not likely to ever produce accurate estimates for sustained vapor extraction system performance, it does provide a quick means of estimating maximum system performance; no system could ever perform better than this reference performance. The

removal rate given by equation [3.28] might also be regarded as an estimate of what might be observed when a system is first turned on, before compositional changes and mass-transfer limitations act to reduce the removal rate with time.

3.2.9 One-Dimensional Models - Equilibrium-Based Well-Mixed Systems

The next level of sophistication in modeling removal due to volatilization is to incorporate compositional changes with time. In this approach, the equilibrium partitioning model described in Subsection 3.2.2 is used and the subsurface is treated as a well-mixed system. Changes in the amount of residual contaminant over time are then described by:

$$\frac{\partial(V_{soil}T_j)}{\partial t} = -QG_j - \lambda f(T_j) \qquad [3.30]$$

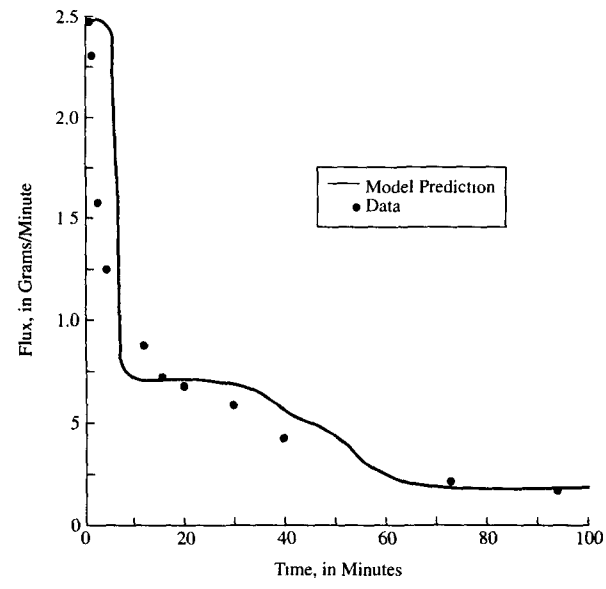
where all variables are as defined above, with $\lambda f(T_j)$ representing losses due to biodegradation. This approach has been used by Baehr, Hoag, and Marley (1989) to describe the variation in effluent concentration for column-venting experiments with gasoline-contaminated sand. Figure 3.16 (on page 3.44) is a plot of the total hydrocarbon removal rate as a function of time for one of the experiments. In this experiment, airflow was held constant and all air passing through the column was in contact with gasoline-contaminated pore space. The decline in removal rate was due entirely to weathering of the residual gasoline; as more volatile hydrocarbons were removed, total hydrocarbon concentration in the pore space declined because of compositional changes. Humps in the model prediction curve presented in figure 3.16 (on page 3.41) are due to removal of constituent classes from the residual product. This approach was used also by Johnson, Kemblowski, and Colthart (1988) and Johnson et al. (1990, 1992) to develop a screening-level design criteria for vapor extraction systems. They used the model to predict a minimum vapor volume requirement α (cm^3-vapor/g-initial residual) to achieve a desired level of cleanup. Predicted values of α, for gasoline, for example, range from 25,000 to 125,000 cm^3-vapor/g-initial residual (400 to 2,000 ft^3-vapor/lb-initial residual), depending on the grade of gasoline and degree of preweathering in the subsurface. The minimum cleanup time estimate τ is given by:

$$\tau = \frac{V_{soil} < T_j > \alpha}{Q} \qquad [3.31]$$

Alternately, one could use equation [3.31] to establish a minimum vapor-flow requirement Q to achieve cleanup in a specified time. The reader is cautioned that equation [3.31] is a lower-bound estimate of the cleanup time and is intended only for screening-level evaluation.

If it is assumed that chemical equilibria between phases in the soil matrix are described by linear relationships and that the system is well-mixed, then equation [3.30] can be solved. It can be observed that this solution will predict soil and extracted vapor concentrations that decrease exponentially with time, as presented by Roy and Griffin (1991).

Figure 3.16
Comparison of Total Hydrocarbon Fluxes from Steady-Flow Venting Experiments to Predictions Obtained from the Mathematical Model



Flow rate = 1.43 L/min

Source. Baehr, Hoag, and Marley 1989

3.2.10 Two-Dimensional Model - Cleanup Along Streamlines

The concept introduced in Subsection 3.2.9 of a minimum vapor volume requirement α (cm^3-vapor/g-initial residual) to achieve a desired level of cleanup can be built upon to develop a transient model for remediation along a streamline, or flow path. In this model, clean air enters at the edge of the contaminated zone and a "cleaning front" propagates toward the extraction point.

Let α (cm^3-vapor/g-initial residual) denote the volume of vapor required to achieve the desired remediation per unit mass of residual hydrocarbon. This parameter may be determined from a lab experiment or by modeling (as described above). Then, if <T> (g/cm^3-soil) denotes the volumetric hydrocarbon concentration, q (cm/s) the specific discharge, t (s) time, and ξ the location of the cleaning front, then:

$$\frac{d\xi}{dt} = \frac{q}{<T>\alpha} \qquad [3.32]$$

Consider one-dimensional radial flow to a vertical well in which $-q = Q/(2\pi rH)$, and Q (cm^3/s), r (cm), and H (cm) denote the total volumetric flow rate to the well, distance from the well, and thickness of the permeable zone, respectively. Equation [3.32] becomes:

$$\frac{dr}{dt} = -\frac{Q}{2\pi rH<T>\alpha} \qquad [3.33]$$

The solution is:

$$r^2 = R_o^2 - \frac{Qt}{\pi H<T>\alpha} \qquad [3.34]$$

where R_o is the radius of the immiscible contamination away from the extraction point at t = 0. Equation [3.34] implies that the time required to clean the flow path τ for this example is given by:

$$\tau = \frac{\pi R_o^2 H<T>\alpha}{Q} \qquad [3.35]$$

which the reader can verify is equivalent to equation [3.31].

A two-dimensional analysis using proof similar to that of the above one-dimensional analysis was used by Johnson and Ettinger (1994) to predict the performance of a vapor extraction trench.

3.2.11 Mass-Transfer Limitations, Nonideal Scenarios, and Transient Effects

The performance of vapor extraction systems under ideal conditions where the induced vapor flow passes through the contaminant source and there is equilibrium partitioning was estimated in the preceding sections. Scenarios where this may not be the case are considered in this section. Figure 3.17 (on page 3.47) illustrates three common scenarios where the removal rates inherently must be less than that predicted by the ideal models presented above. Geological heterogeneities also frequently result in non-ideal conditions.

In the scenario depicted in figure 3.17a, a fraction ϕ of the air drawn through the soil bypasses the contaminant zone as a result of nonhomogeneous contaminant distribution or improper extraction well placement. Clean air reaching the extraction well then dilutes the contaminant-laden vapors in the extraction well. An estimate of the removal rate R (g-j/cm^2-s) is then:

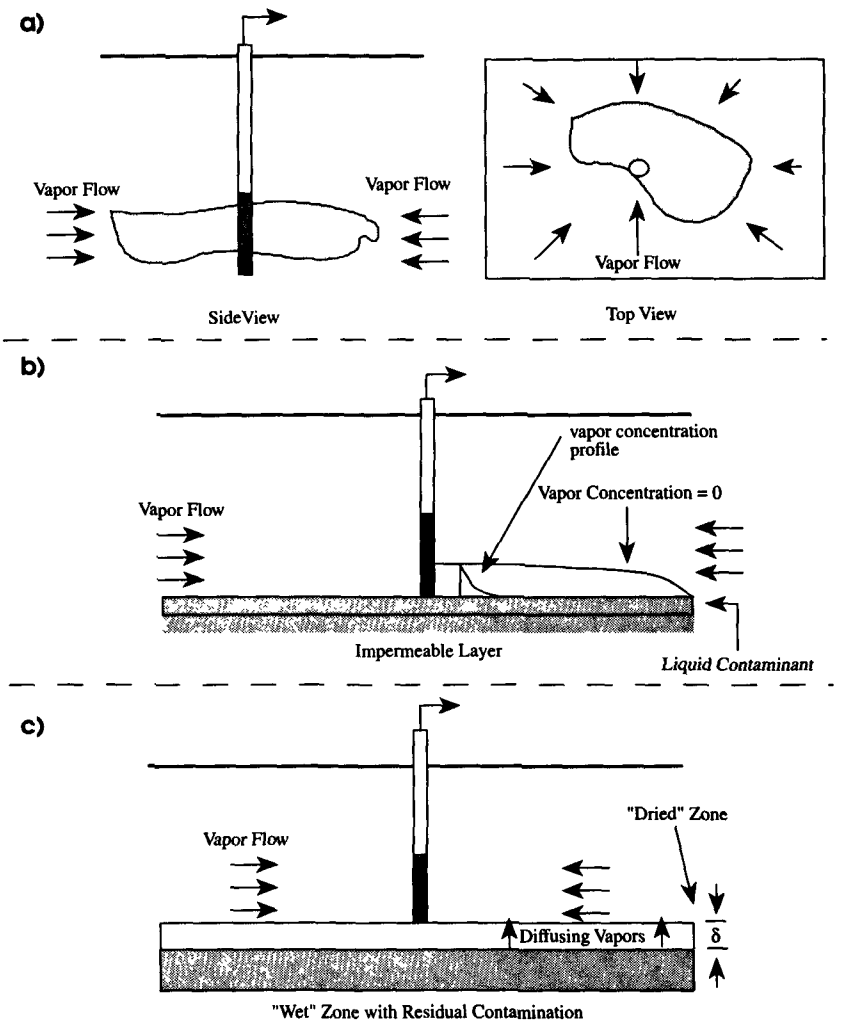
$$R = (1-\phi)R_{max} \qquad [3.36]$$

where R_{max} (g-j/s) represents the removal rate estimated for the ideal case. The corresponding time for cleanup τ (s) estimate is increased relative to the minimum cleanup time estimate τ_{min} (s) by:

$$\tau = \frac{\tau_{min}}{(1-\phi)} \qquad [3.37]$$

In the scenarios of figures 3.17b and 3.17c, the induced vapor flow path parallels the residual contaminant but does not pass through it. This might occur with flow past pooled liquid contaminant (figure 3.17b) or with contaminants trapped in low-permeability zones surrounded by more permeable layers. In these instances, the removal rate is limited by vapor-phase diffu-

Figure 3.17
Limiting Model Scenarios for Removal Rate Estimates



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sion, which is usually described in terms of an effective diffusion coefficient D^{eff} (cm^2/s). The diffusive flux F_j (g-j/cm^2-s) across an incremental distance Δx (cm) can be written:

$$F_j = -D^{eff} \frac{\Delta G_j}{\Delta x} \qquad [3.38]$$

where ΔG_j (g-j/cm^3-vapor) denotes the change in vapor concentration across that distance.

For the scenario depicted in figure 3.17b (on page 3.47) and one-dimensional radial-flow, Johnson et al. (1990) solved equation [3.27] to derive an efficiency factor η relative to the ideal case ($R = QG_j$) for a single component contaminant pool:

$$\eta = \frac{1}{3H}\sqrt{\frac{6D^{eff}\mu}{k}\left[\frac{\ln\left(R_{atm}/R_{well}\right)}{\left(P_{atm}-P_{well}\right)}\right]\left(R_2^2 - R_1^2\right)} \qquad [3.39]$$

where:

D^{eff}	= effective diffusion coefficient (cm^2/s),
H	= thickness of zone permeable to airflow (cm),
μ	= vapor viscosity (g/cm-s) $\approx$0.00018 g/cm-s,
k	= permeability to vapor flow (cm^2),
R_{atm}	= radius of pressure influence of extraction well (cm),
R_{well}	= well radius (cm),
P_{atm}	= atmospheric pressure (1.016×10^6 g/cm-s^2),
P_{well}	= absolute pressure at venting well (g/cm-s^2), and
$R_1 < r < R_2$	defines the region in which contaminant is present.

As an example, consider a 5.1 cm (2 in.) radius vapor extraction well installed in a sandy soil ($k = 1 \times 10^{-8}$ cm^2 (1×10^{-11} ft^2)) with a blower connected to maintain a 0.90 atm (0.91×10^6 g/cm-s^2 (1.5 lb/in.^{2} = 41 in. H_2O gauge-vacuum)) pressure at the well. The objective is to remediate a zone

extending to R_2 = 900 cm (30 ft) from the well. Assuming that H = 300 cm (10 ft), R_{atm} = 1,200 cm (40 ft), and D^{eff} = 0.0014 cm^2/s (1.5 x 10^{-6} ft^2/s) then equation [3.39] predicts the removal rate will be only 9% of the ideal case removal rate.

Figure 3.17c (on page 3.47) is representative of the situation wherein a clay lens containing residual contamination is surrounded by more permeable sandy soils. In the model of Johnson et al. (1990), a drying front develops in the less-permeable zone and grows away from the permeable/ impermeable soil interface. Thus, the distance over which vapors diffuse to reach the flowing-vapor stream increases with time; consequently, as predicted by equation [3.38], the rate of removal R (g/s) decreases with time:

$$R = \pi\left(R_2^2 - R_1^2\right)\sqrt{\frac{G_J D^{eff} T_J \rho_b}{2t}} \qquad [3.40]$$

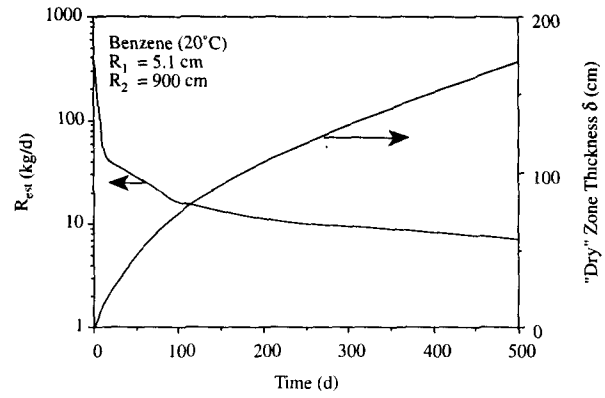
where all variables are as defined above. The corresponding drying zone thickness δ (cm) is given by:

$$\delta(t) = \sqrt{\frac{2G_J D^{eff} t}{T_J \rho_b}} \qquad [3.41]$$

Figure 3.18 (on page 3.50) presents results of a sample calculation for benzene (G_J = 0.00032 g/cm^3 @20°C (0.02 lb/ft^3)) at a residual level of T_J = 0.017 g/cm^3 (1.1 lb/ft^3) and R_2 = 900 cm (30 ft). These results indicate it would take approximately one year to clean a 150 cm (5 ft) layer.

Equation [3.41] predicts a removal rate vs. time dependence that is very similar to what is observed at many vapor extraction sites, although the decline with time is typically attributed to changes in the residual composition. Diffusion limitations can also produce the same apparent behavior; thus, care must be taken to not over interpret field data. For example, vapor composition analyses with time are necessary to distinguish between the two phenomena; mass-transfer limited scenarios are often characterized by large decreases in removal rate without accompanying significant changes in composition.

Figure 3.18
Estimated Maximum Removal Rates and Residual Hydrocarbon Reduction for a Venting Operation Limited by Diffusion.



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It is also possible to observe very rapid declines in removal rate with time during the first few days of operation of a vapor extraction system that is not attributed to either phenomenon discussed above. Usually, this is an indication that the airflow has swept those contaminant vapors that had originally diffused away from the vapor source back to the extraction point. Once the first few "pore volumes" of vapors are removed from the subsurface, decreases in removal rate with time tend to be less drastic, unless accompanied by significant changes in water-table height, vapor flow-rate, etc.

3.2.12 Microbiological Processes (Bioventing)

As explained in Section 3.1, inducing vapor flow through the subsurface not only increases removal rates through volatilization, but also enhances aerobic microbial degradation as a result of accelerating the resupply of oxygen to the subsurface. Bacteria utilize oxygen to break down degrad-

able contaminants into carbon dioxide, water, and biomass (cells); for example, consider the degradation of n-hexane:

$$C_6H_{14} + \frac{19}{2}O_2 \rightarrow 6CO_2 + 7H_2O + biomass \qquad [3.42]$$

Based on equation [3.42], 3.5 g-O_2 are required per gram of n-hexane degraded. In recent years, numerous laboratory-scale investigations have been conducted in order to study the aerobic degradation of hydrocarbons and the effects of changes in moisture content, nutrient addition, contaminant concentration and composition, and other process variables on degradation rate. Results indicate that many contaminants of concern are biodegradable and indigenous microorganism populations can carry out the task, if subsurface conditions are amenable. In this monograph, bioremediation is discussed only as it relates to soil vapor extraction. The reader is referred to the monograph in this series, *Innovative Site Remediation Technology: BIOREMEDIATION*, for an in-depth presentation of bioremediation.

Quantifying degradation rates in the field can be difficult, and the data are often subject to a range of interpretations. As equation [3.42] indicates, assessment can be based on contaminant disappearance (soil sampling), oxygen gas depletion (soil-gas sampling), or carbon dioxide gas formation (soil-gas sampling). Since there is inherently a large degree of uncertainty associated with the first option, reported bioventing rates are typically based on results of soil-gas analyses combined with theory. The monitoring and interpretation of field data are discussed in detail in Section 3.6. Final verification is generally based on soil core analysis after prolonged operation (months).

Microbiological activity has been reported at temperatures varying from -12° to 100°C (54° to 212°F) (Brock, 1970); however, the optimal range for biodegradation of most contaminants is much narrower. Individual microorganisms may tolerate a temperature range of up to about 40°C (104°F). Generally, biodegradation rates double for every 10°C (5~°F) temperature increase, up to some inhibitive temperature. The van't Hoff-Arrhenius equation expresses this relationship quantitatively as:

$$Y = Ae^{-E_a/RT} \qquad [3.43]$$

where:

Y = temperature-corrected biodegradation rate,

A = baseline reaction rate,

E_a = activation energy,

R = gas constant, and

T = absolute temperature.

Miller (1990) found E_a equal to 8 to 13 kcal/mole for in situ biodegradation of jet fuel. In the 17° to 27°C (63° to 81°F) range, the van't Hoff-Arrhenius relationship accurately predicted biodegradation rates.

Figure 3.19 (on page 3.53) illustrates the effect of temperature on JP-4 jet fuel biodegradation in soils collected from Eielson Air Force Base near Fairbanks, Alaska. See also figure 3.20 (on page 3.55). The colder-region organisms biodegrade jet fuel at higher rates at 20°C (68°F) than do organisms adapted to temperate climates.

3.2.13 Air Injection Below the Groundwater Table

The capacity of an air-sparging system for volatilizing hydrocarbons in the saturated zone or resupplying an aquifer with oxygen is dependent upon the way in which the air is distributed when injected into the saturated zone. Although it is convenient to visualize uniform bubbles simply rising upward and outward from air injection points, the actual air distribution patterns are likely to be quite complex. A working description of the likely flow and distribution of injected air and its effect on system performance follows.

In order for air to be injected beneath the groundwater table, air must first displace water from the injection well, the air-sparging well packing (or diffuser), and the formation. At a minimum, therefore, an initial pressure P_{min} (g/cm-s^2) is required equal to:

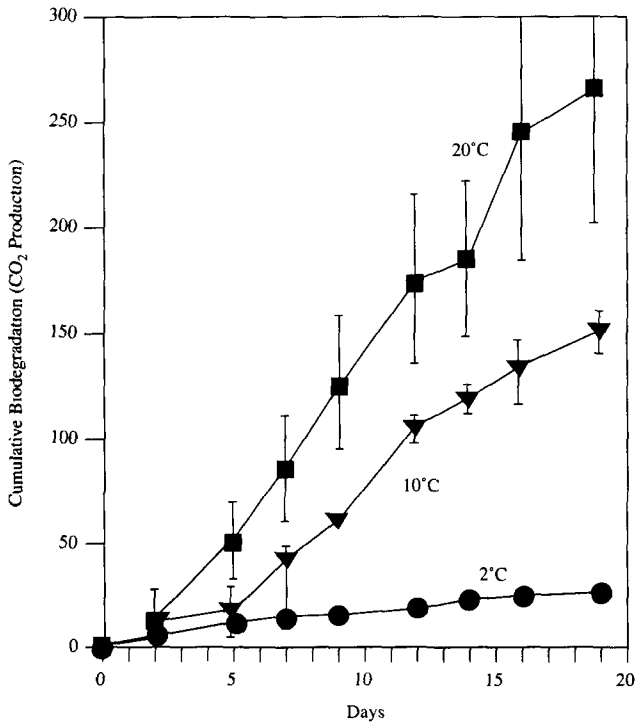
$$P_{\min} = \rho_{water} g H_{water} + P_{diffuser} + P_{soil} \qquad [3.44]$$

where:

ρ_{water} = density of water (1 g/cm^3),

g = acceleration due to gravity (980 cm/s^2),

Figure 3.19
Biodegradation of JP-4 Jet Fuel in Soils Collected Near Fairbanks, Alaska



Source: Wyza and Hinchee 1990

H_{water} = depth below water table to top of injection well screen (or diffuser) (cm),

$P_{diffuser}$ = air-entry pressure for injection well packing or diffuser (g/cm-s^2), and

P_{soil} = air entry pressure for the formation (g/cm-s^2).

Equation [3.44] can also be written in terms of pressure head, where the pressure head H_i, expressed as a height of water column is related to the pressure P_i by:

$$H_i = \frac{P_i}{\rho_{water} g} \qquad [3.45]$$

Equation [3.44] becomes:

$$H_{\min} = H_{water} + H_{diffuser} + H_{soil} \qquad [3.46]$$

and H_{min}, $H_{diffuser}$, and H_{soil} denote the minimum pressure head for sparging, air-entry pressure head for the diffuser (or packing), and air-entry pressure head for the formation, respectively. For reference, 1 atm = 1 x 10^6 g/cm-s^2 (33.9 ft H_2O).

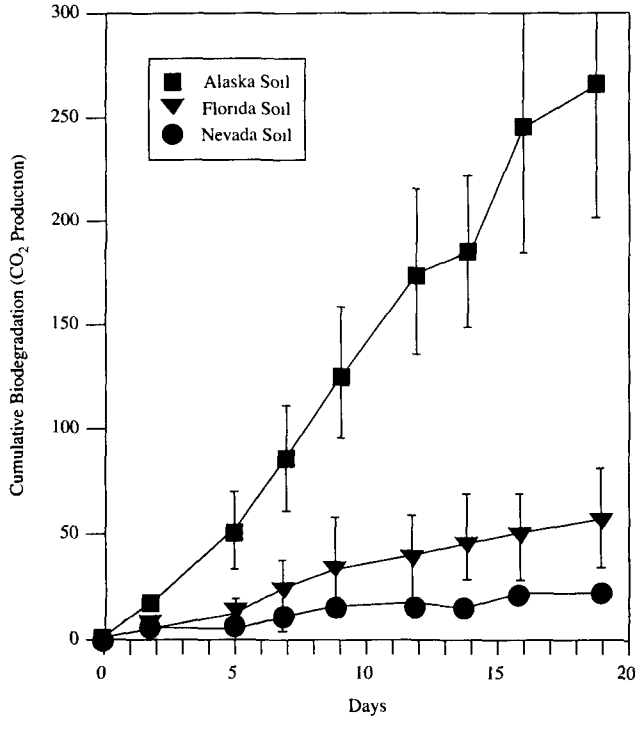
The air-entry pressure required varies with the type of soil, with values ranging from approximately 1 cm (0.4 in.) for coarse sands to >1 m (1.1 yd) for very fine-grained soils, such as silts and clays. In practice, one often encounters layered lithologies.

The relationship between the three factors dictating the minimum sparging pressure, H_{min}, has implications also for the distribution of air in the vicinity of the sparging well. When H_{water} is much greater than $H_{diffuser}$ and H_{soil}, it is likely that air will enter the formation primarily near the top of the sparging well screen. Thus, if standard well constructions (i.e., slotted pipe surrounded by a sandy packing material) are used in coarse soils, it does not make much sense to extend the well screen to more than about 1 meter. To achieve more uniform distribution of air entry across the air injection well, therefore, it is necessary to increase the value of $H_{diffuser}$, which can be accomplished either by increasing the resistance to airflow across the well screen (using a diffuser) or by using a much finer well packing material.

As air enters the formation at the injection well, it displaces water and begins to travel outward and upward toward the vadose zone as a result of the applied pressure, buoyancy forces, and macroscale characteristics of the formation. Normally, uniform displacement fronts are envisioned when one fluid displaces another in a porous medium; however, in this case a much

different air-flow path results because the air is much less viscous than water and the formation is more permeable to airflow than water under typical sparging conditions. The air is said to have greater "mobility" than the displaced water and therefore, the flow is "unstable" because even very small heterogeneities in the formation cause preferential air-flow channeling through "fingers" (see figure 3.21 on page 3.56). Channeling becomes more pronounced as the degree of heterogeneity increases. Air injection may also cause soil fracturing and weakening of the soil stability.

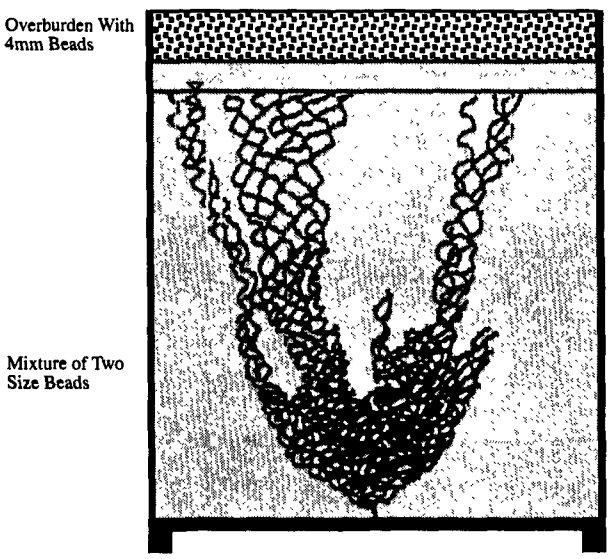
Figure 3.20
Biodegradation of JP-4 Jet Fuel at 20°C in Various Soils Collected Near Fairbanks, Alaska; Fallon, Nevada; and Panama City, Florida



Source. Wyza and Hinchee 1990

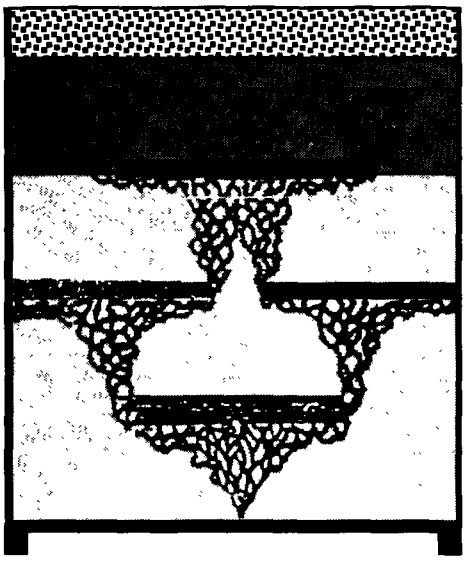
Large-scale variations in the formation, such as those caused by distinct strata or lenses, where the less-permeable (and higher air entry pressure) strata are not continuous and the air passes around the units as it finds a pathway through the saturated zone, will also affect the air distribution, as illustrated in figure 3.22 (on page 3.57). Now consider the effect on the path when air is injected into a stratum of greater permeability than the continuous stratum lying above it. An air "bubble" will spread horizontally beneath the less permeable layer until the pressure in the bubble increases to the air-entry pressure of the confining unit or until it intercepts a permeable vertical pathway (such as a monitoring well). The practitioner must be aware that this vapor-flow distribution may actually result in increased transport of hydrocarbon away from the source.

Figure 3.21
Observed Air Channel Pattern in Uniform Mixture of 0.75 and 0.3 mm Glass Beads



Source: Ji et al. 1993

Figure 3.22
Observed Air Channel Pattern in Stratified Medium



Source: Ji et al. 1993

The foregoing discussion may help provide an intuitive picture of air distribution and flow resulting from air injection beneath the water table and roughly identify inherent advantages and limitations of this technology. Given current limitations, the exact numbers, size, or spacing of air channels that are likely to be formed during air sparging cannot be predicted. Nonetheless, the formation of distinct air channels (as opposed to bubbles) significantly affects the capacity of the system for maximizing the rate of volatilization and enhancing microbial degradation of residuals trapped beneath the groundwater table. In the flow visualization work of Ji et al. (1993), small bubbles were observed only when glass bead diameters were >2 mm (0.08 in.). Given the transport discussion in Subsections 3.2.8 through 3.2.11, effective remediation of residuals trapped within the air channels can be expected, but removal of contaminants from water satu-

rated zones will be limited severely by diffusion limitations, unless significant mixing of the water-saturated zones is induced by the airflow (e.g., pulsed sparging). Similarly, the transport of oxygen into the water-saturated formation will be limited by diffusive processes. The removal of hydrocarbons from low permeability unsaturated formations by diffusive processes was discussed in Subsection 3.2.11 (see equation [3.40], for example). That scenario is similar to that of the volatilization of hydrocarbons from a water-saturated zone into an air channel. Removal rates from water-saturated zones, however, are expected to be much lower, as diffusion coefficients in water are four orders of magnitude less than diffusion coefficients in air.

3.3 Characterization Activities

Competent characterization of the site and assessment of the hydrocarbons present are needed to provide sufficient information to assess the feasibility of vapor extraction-based technologies and to design effective remedial systems. As will be shown in Section 3.4, there are a number of different methods for assessing feasibility and designing systems, and each practitioner must select the approach that best meets the requirements and constraints of a given site. Data requirements vary from site to site and consequently, a fixed set of actions will not be prescribed here. Instead, a range of characterization steps will be presented in this section from which the reader may select after identifying his or her particular data requirements based on the guidance given in Section 3.4. In addition, this section will illustrate the effective presentation of information so that it can be used in the feasibility screening and design process described in Section 3.4.

A sequence of characterization activities is outlined in table 3.3 (on page 3.59), in order of priority based on needs for feasibility screening and design and, to some degree, on the difficulty of obtaining the information. Each of the characterization activities is discussed and a few common methods for performing each are briefly described below; however, the reader should note that there is a wide range of tools that can be used to meet many of the data collection objectives. For a general introduction to site assessment activities, see the API Publication 1628: *A Guide to the Assessment and Remediation of Underground Petroleum Releases.*

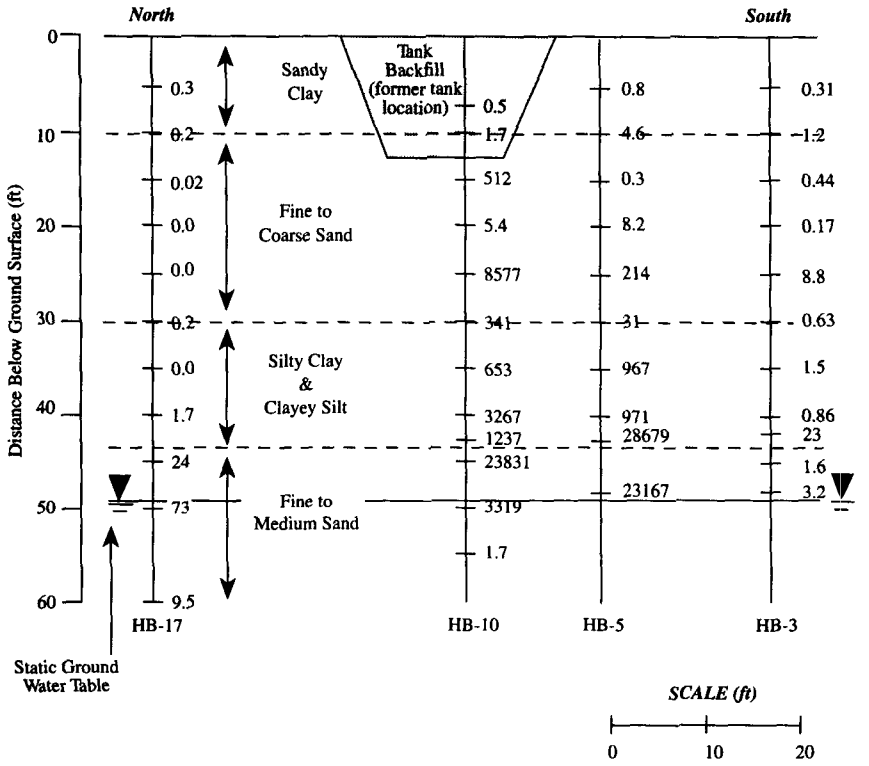
3.3.1 Contaminant Assessment

The goal of the contaminant assessment is to: (1) develop a "picture" of the subsurface, such as that shown in figure 3.23 (on page 3.60), where the contaminant distribution is superimposed upon the geological cross-section

Table 3.3
Site Characterization Activities

Activity #	Description	Data Reduction and Presentation Requirements
	Preliminary Characterization Activities	
1	Hydrocarbon Assessment (See §3 3 1) • vertical/horizontal delineation • hydrocarbon characterization (type, boiling point distribution, regulated component identification)	See figure 3.23 See figure 3.24
2	Geologic/Hydrogeologic Assessment (See §3 3 2) • identification of soil strata • permeability assessment (core tests, sieve analysis, etc) • static water table determination (and seasonal fluctuations) • subsurface conduits, piping, tanks, obstructions, etc	See figure 3 23
	Laboratory Characterization Activities (See §3.3.3)	
3	Laboratory Soil Column Feasibility Studies (optional)	See figure 3 26
	Field Pilot-Scale Activities (See §3.3.4)	
4	Airflow -vs- Applied Pressure/Vacuum Test • vacuum test for vapor extraction wells • pressure test for air injection wells	See figure 3 28
5	Effluent Vapor Characterization -vs- Time • total hydrocarbon concentrations • regulated compound speciation • hydrocarbon characterization (i.e. boiling point distribution) • O_2/CO_2 speciation	See figure 3 30
6	Subsurface Pressure Distribution • as function of depth and distance • steady-state and transient measurements	See figure 3.32
7	Subsurface Vapor Concentration Distribution • as function of depth and distance • hydrocarbon concentrations and composition • O_2/CO_2 speciation	See figure 3.33
8	Groundwater Elevation Changes Resulting from Air Extraction/Injection	See figure 3.35
9	Groundwater Monitoring • hydrocarbon levels • dissolved oxygen	See figure 3.36
10	Tracer Gas Tests	See figure 3 37

Figure 3.23
Recommended Presentation of Total Hydrocarbon Distribution and Subsurface Geology.



Soil concentrations given in mg/kg-soil.

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of the area to be treated and (2), sufficiently characterize the contaminant so that an assessment of its treatability can be made. Possible contaminant characterization methods are described and possible approaches for determining the spatial extent of contaminants are discussed in this subsection and characterizing the subsurface is discussed in Subsection 3.3.2.

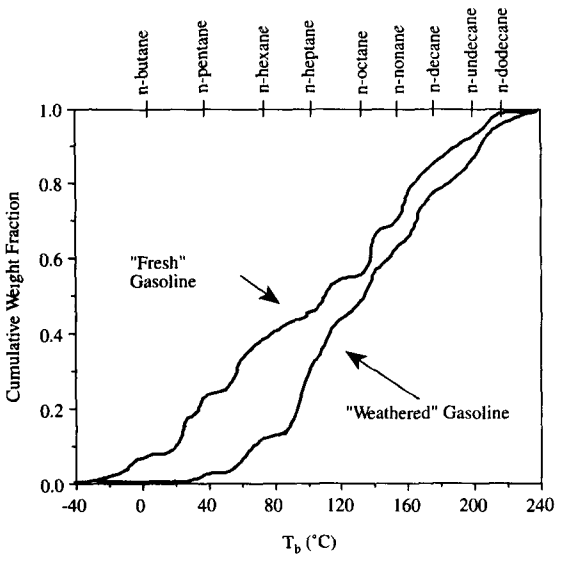
Under the current state-of-the-practice, contaminant composition is assessed based on results of laboratory analyses of soil and groundwater samples obtained from soil borings and groundwater monitoring wells. Laboratories are most often requested to analyze samples for total petroleum hydrocarbons (TPH) and specific compounds of regulatory interest (e.g., benzene). Recall, however, that the performance of vapor extraction-based technologies is linked to the partitioning of contaminants in the subsurface and the partitioning of any single compound may be dependent on all others present in the matrix (see Section 3.2). Thus, while typical laboratory analyses have some value from a regulatory perspective, they provide an incomplete picture for the purposes of feasibility screening and design. Because a complete analysis of many contaminant mixtures is not practicable (e.g., there are >100 components in a typical gasoline), simpler cost-effective methods for providing the needed information are sought. One of these is the characterization of contaminant distributions by boiling point fractionation, represented in figure 3.24 (on page 3.62). This can be done in a number of ways; the simple method presented below utilizes laboratory results that are generated in standard analyses, but are not reported.

In the course of many routine contaminant analyses a liquid or vapor contaminant sample is injected into a gas chromatograph equipped with a flame ionization detector (GC-FID). The chromatographic column then separates contaminant components as they are swept by a carrier gas toward the detector, which provides an electrical signal reflecting intensity vs. time to a recorder/integrator. Concentrations are assigned to individual components with knowledge of their elution/retention time and intensity vs. concentration calibrations. When requested to report the concentrations of individual components, laboratories focus on specific peaks and ignore the rest of the chromatograph. If, however, the elution times of a series of "marker" compounds (e.g., a series of normal alkanes: methane, ethane, propane, n-butane, etc.), are known then the sum of all contaminants that elute between two known compounds can be quantified and expressed as a fraction of the total contaminants detected. For characterization purposes then, these fractions or groups of compounds, can be treated as "pseudo-compounds," having chemical properties that are some average of the two bounding marker compounds. For example, if boiling point ranges are assigned to these fractions, a "boiling point curve" such as that shown in figure 3.24 (on page 3.62) can be generated. This information provides a valuable picture of the distribution of contaminants in a mixture and can be

used to carry out some of the partitioning calculations outlined in Subsection 3.2.2. This approach is illustrated by Johnson et al. (1990), who compare predictions for a gasoline mixture of 72 hydrocarbons with that of an equivalent nine-component approximate mixture.

It should be noted that the characterization method described above is especially useful in assessing the behavior of complex mixtures in processes that are governed by component vapor pressures (e.g., soil vapor extraction of typical residual levels of hydrocarbons); this is because compounds are roughly separated by vapor pressure in a GC-FID analysis. The same is not true for processes governed by solubility or partitioning from an aqueous phase, unless the contaminant mixture is composed of components having chemical structures similar to the marker compounds. For example, in

Figure 3.24
Boiling Point Distribution Curves for Samples of "Fresh" and "Weathered" Gasolines



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gasoline there is a mixture of aromatic and aliphatic hydrocarbons, of which the aromatic compounds are by far the most soluble. If the method given above is followed and fractions are characterized by a series of n-alkanes, the average solubility value assigned to fractions containing the aromatic compounds will be a significant underestimation of their true equilibrium partitioning into an aqueous phase. In the absence of any knowledge of the contaminant mixture, one empirical method of working around this problem is to perform a second GC-FID analysis on a "small" aqueous sample that has been allowed to equilibrate with a "large" hydrocarbon sample previously characterized by the above method. As in the residual analysis described above, the chromatographic output from the aqueous phase analysis is again divided by hydrocarbon fractions and the concentration in each fraction is quantified. For partitioning calculations then, the "pseudo-compound" solubilities are set equal to the measured concentrations from this experiment.

In determining the spatial distribution of contaminants, first, the areal extent of contamination is assessed (horizontal delineation), and then a vertical profile of the area is determined. Detailed contaminant composition analyses (such as that described above) are time-consuming and costly, but are fortunately needed for only a limited number of samples when investigating single-source release sites. There are a number of field investigation methods for contaminant delineation that vary in terms of cost, ease, reliability, ability to provide information on vertical definition, and use of existing wells. The object is to increase the speed of sample collection or decrease the complexity and cost of analyses and to this end, the preferred methods often involve some cost-saving gross measurement of contaminant concentrations, such as TPH or the detection of some easily identifiable "marker" compound, such as a highly-volatile or highly-soluble component. See table 3.4 (on page 3.64) for qualitative assessments of the performance of a number of these methods, which are briefly described below.

Soil-Gas Surveys. In a soil-gas survey, a hollow tube with a sampling interval at the bottom (slots or holes) is driven into the soil. A vapor sample is then drawn up through the tube and collected for laboratory analysis or direct field analysis. Complex soil-gas surveys involve multi-level sampling of many areas; however, for site screening, "shallow" soil-gas sampling (<1.5 m (5 ft) BGS) is most often practiced. A positive result (i.e., detectable contaminant vapors) of a soil-gas analysis is a reliable indicator of the presence of contaminants somewhere in the subsurface; unfor-

Table 3.4
Methods for Hydrocarbon Delineation

Method	Ease	Cost	Reliability		Vertical Definition	
			Vadose[1]	GW[2]	Vadose[1]	GW[2]
Soil Gas Survey	High	Low	Low	Low	Possible	No
Product Thickness	High	Low	Moderate	Moderate	No	No
Groundwater Sampling	High	Moderate	Low	High	No	Possible
Cone Penetrometer	Moderate	Moderate	High	High	Yes	Yes
Soil Sampling	Low	High	Moderate	Moderate	Yes	Yes

1 - unsaturated zone characterization
2 - saturated zone characterization

tunately, a negative result cannot be interpreted to indicate the absence of contaminants, except in the very localized sampling area. Soil-gas sampling can be performed relatively rapidly and at a low cost; however, proper analysis requires knowledge of the subsurface geology and contaminant composition. Deeper soil-gas surveying has been reported successful for dissolved contaminant plume delineation, although this conclusion is not widely accepted (soil-gas surveying may prove to be useful for shallow, soluble groundwater plumes or free-phase liquid plumes). It is most likely to be effective for the detection of volatile compounds in relatively permeable and homogeneous soils or in other words, in those scenarios favorable for the application of vapor extraction-based technologies. If sampling and analysis are performed properly, soil-gas data provide a direct assessment of the maximum extractable contaminant vapor concentrations that could be measured at the start of a vapor extraction operation. However, it should be noted that no quantitative correlation exists between measured soil-gas concentrations and hydrocarbon levels in soils for high concentrations of residual contaminants (a conclusion supported by the equilibrium partitioning analysis presented in Section 3.2). Soil-gas surveys are also limited by materials that the probes can be pushed through, and may not be practicable in areas of urban fill (concrete, rubble, and brick).

Product Thickness Measurements. The appearance of free-phase liquid contaminants in monitoring wells indicates soils highly saturated with contaminants near or below the water table; but it does not give any indication of the extent of contaminants in the vadose zone. Where there are LNAPLs, visible free-phase contaminants indicate that the contaminants are distributed at or near the water table (or capillary fringe). If the contaminant has been present for a while, there is also a high probability of residually-saturated soils above and below the water table because "smearing" of LNAPL during the rise and fall of the water table over the hydrogeological cycle. The presence of DNAPLs also indicates contaminant-saturated soils at or below the water table; however, the densities of these materials do not constrain them to the water table interface.

Groundwater Sampling. Unless residual contamination is known to have affected groundwater (i.e., free-phase mobile LNAPL or DNAPL is present), groundwater sampling results are of limited value in delineating unsaturated zone contamination. Groundwater levels respond to soil contamination if: (1) groundwater is in contact with the impacted soil, (2) there is significant recharge that leaches through impacted soils, or (3) there is significant contaminant vapor migration. As in soil-gas sampling, therefore, positive results indicate the presence of contaminants somewhere in the subsurface, but the absence of measured dissolved contaminant plumes does not necessarily indicate the absence of vadose zone contamination.

Groundwater sampling results are valuable for use in mapping contaminants beneath the water table if there is some presampling knowledge of the vertical contaminant distribution. Where LNAPLs are known to be present, the focus is on sampling groundwater in the vicinity of the water table (or the zone over which the groundwater level has fluctuated) because that is the zone in which LNAPLs are most likely to be present. Distribution of DNAPLs is strongly dependent on the release size and the subsurface geology. The ability to predict their probable location is limited, except where distinct confining strata are present.

Groundwater samples can be obtained from traditional monitoring wells or through use of newer sampling methods, such as the cone penetrometer, or of the direct-push technologies (Geoprobe™, Hydropunch™, etc.).

Cone Penetrometer. The cone penetrometer is a tool adapted from geologic practice that can be used to simultaneously determine subsurface li-

thology and contaminant extent based on soil-gas and groundwater analyses. It typically consists of a narrow (<5-cm (2 in.) diameter) cylindrical rod equipped with pressure transducers and a sampling port. As the rod is driven into the soil, the normal pressure exerted by the soil on the rod tip and tangential resistance exerted on the rod sleeve are recorded and the ratio of the two are related to soil structure. The data is then used to deduce soil properties. More advanced units can perform pore pressure dissipation tests in order to quantify point permeability. The sampling port allows access to the collection of pore water, groundwater, or soil-gas samples. For certain geological conditions (one must be able to drive the cone through the subsurface), the cone penetrometer is an attractive tool for performing rapid preliminary assessments and can be used to identify locations for permanent monitoring wells.

Soil Sampling. Soil sampling refers to the physical collection of soil from below grade by hand augering or other drilling or direct push techniques. Soil samples are collected at selected depth intervals, preserved, and either sent to laboratories for analysis, or analyzed in the field by a screening technique (usually headspace vapor analysis). Soil sampling is the traditional method of contaminant delineation; however, in interpreting the results, the user must be familiar with biases introduced by sample handling practices and soil heterogeneities (which are also present to some degree for all sampling methods).

3.3.2 Geologic/Hydrogeologic Assessment

In a comprehensive geologic/hydrogeologic assessment, one should locate distinct geologic strata, subsurface conduits and obstructions (piping, tanks, etc.), and the water table and determine groundwater gradient, groundwater velocity, and interval of observed water table fluctuations. In addition, knowledge or estimates of the physical properties of each of the strata is needed (e.g., permeability, moisture content, organic carbon fraction). The most important, with respect to vapor-extraction based technologies, is an estimate of the permeability to airflow. This may be obtained through permeability tests on soil cores or estimated through correlations based on grain-size analysis. It should be noted that results from either approach may not always be indicative of actual field conditions, as the lab tests are often performed on disturbed soil samples, and generalized correlations also have some degree of uncertainty. Even when performed on "un-

disturbed" samples, these tests provide only a localized measure of vertical permeability.

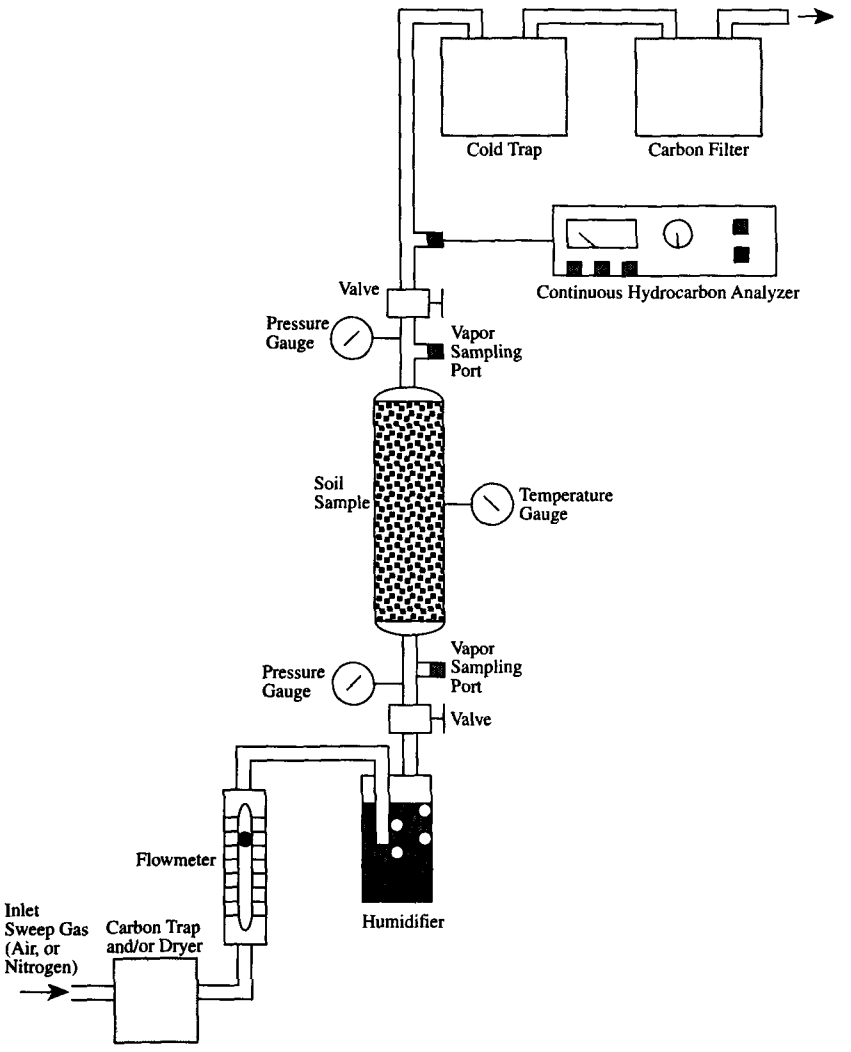
Most geologic cross-sections are currently developed through analysis of drilling logs and site records (of tanks, piping, etc.); although other geophysical techniques, such as the cone penetrometer (see Subsection 3.2.1), are beginning to play a more important role in this aspect of site assessment. If borings are to be drilled, it is worthwhile considering installing monitoring wells, piezometers, or vadose zone monitoring installations in them at the same time, as these will be required if field-pilot testing is conducted.

At this point, it is worthwhile stressing the need to develop detailed geologic cross-sections when considering vapor extraction-based technologies. The level of detail necessary varies with technology; for example, air sparging performance is more affected by subtle permeability changes than vapor extraction or bioventing. At a minimum, distinct geologic units need to be identified so that the system designer can form a clear conceptual picture of the induced airflow. Vapor flow rate and flow path are two of the three most significant factors influencing vapor extraction-based system performance. They are controlled primarily by the site hydrogeology and well construction. Knowledge of subsurface geology is essential for the evaluation of processes using air injection, as there is serious concern that a misapplication of the technology can result in detrimental environmental and health effects. In air sparging, airflow away from the injection well is strongly influenced by relatively minor lithological changes and the identification of possible preferential channels and barriers to flow is critical.

3.3.3 Laboratory Soil Column Tests

In some instances, it becomes necessary to empirically measure, rather than predict, the optimal system performance at a given site. Historically, such cases have comprised a small percentage of the total number of vacuum vapor applications. Most are associated with sites where remedial cost estimates are very large, and it is very important that realistic performance expectations be determined. Bench-scale experiments might also be a cost-effective means of identifying how changing process conditions might affect field-scale performance. For example, the effect of variations in flow rate on possible micro-scale (intraparticle) mass transfer limitations could be studied. Historically, bench-scale treatability tests have been of the kind depicted in Figure 3.25 (on page 3.68). Here, a core of the material

Figure 3.25
Basic Laboratory Soil Column Treatability Test Schematic



to be treated is placed in a soil column, or series of columns. Each column is configured so that air flows in one end of the column and out the other, either by applying a pressure or a vacuum to one end. Flow rates, pressures, and contaminant concentrations in the vapor streams may be measured during the test. Soil samples are analyzed before and after the test.

However, it must be recognized that laboratory tests are being conducted on disturbed soil samples that are inherently unrepresentative of field conditions for a number of reasons. Data from such tests have historically been overemphasized and misinterpreted. Even if intact cores are used, air is constrained to flow vertically in the laboratory test, which is not likely the primary air-flow direction in the field. Thus, it is arguable that air permeability, mass-transfer limitations, and "real-time" loss rates cannot be realistically measured in the laboratory-scale test depicted in figure 3.25 (on page 3.66). In addition, it must be remembered that the sample to be tested is only representative of a very localized area of the site under consideration.

There are many reasons that bench-scale laboratory tests are rarely performed. Two obvious ones are cost and time. However, there also significant state-of-the-art limitations in the ability to properly extrapolate bench-scale results to field designs. Two of the most important factors in any in situ remedial technology application — *macro-scale mass transfer* limitations and geological heterogeneity are not represented in typical soil column type experiments. A case in point is the work by Hinchee and Arthur (1991). They found that in soil column experiments that the application of nutrients increased the rate of biodegradation in Hill AFB soil samples. Dupont, Doucette, and Hinchee (1991), however, found that nutrient addition in the field had no effect on bioventing rates.

The true value of laboratory column tests is that they enable one to determine achievable cleanup levels, assess the accuracy of chemical partitioning models that might be used for predictive purposes, and to approximate potential biodegradation rates. The goal, then, is to conduct the tests in a manner that allows simulation of the most efficient hydrocarbon removal in the field. This is accomplished with low vapor flow rates. The evaluation of pore-scale equilibrium presented by Johnson et al. (1990) suggests that pore velocities less than 0.1 cm/sec are appropriate and this is roughly equivalent to a flow rate per unit cross-sectional area of 0.03 cm^3/cm^2-s (0.06 ft^3/ft^2-min). In any case, practitioners should ensure that velocities bench-scale tests are representative of expected full-scale field conditions.

Suggested Soil Column Feasibility Test Protocol. A suggested protocol for conducting column tests is given below. This approach differs somewhat from that given in the US EPA's *Guide for Conducting Treatability Studies under CERCLA: Soil Vapor Extraction* (1991b) in that here the use of modeling is less integral to the experimental protocol and adjustments during the test are based solely on experimental data.

1. Calibrate all analytical instruments and process monitors (flow meters, pressure gauges, etc.);
2. Collect representative core samples in the field and ship to testing facility. Assure sample is preserved;
3. Construct five soil columns using 5.1 cm (2 in.) diameter x 31 cm (12.2 in.) glass columns (approximately 1 kg (2.2 lb) soil). Sample each and analyze for:
   - total contamination concentration (using a solvent extraction/ GC method),
   - boiling point distribution (as described in Subsection 3.3.1),
   - compounds of regulatory interest,
   - soil moisture content,
   - organic carbon fraction,
   - bulk density and total porosity, and
   - enumeration of hydrocarbon-degrading bacteria (optional);
4. Based on results of the total hydrocarbon analyses, compute an estimate of the total contaminant mass (mg) in the column $M_{HC}(t = 0) = M_{soil}\, C_{soil}\, (t = 0)$, where M_{soil} is the mass of soil in the column (kg), and $C_{soil}\, (t = 0)$ is the total contaminant concentration (mg/kg) in the soil at the start of the test;
5. Place soil columns in the apparatus shown in figure 3.25 (on page 3.66). Keep inlet and outlet valves closed and allow to equilibrate for at least one hour or until the temperature of the soil core stabilizes at ambient temperature. Then sample the soil gas and analyze for:
   - total contaminant concentration,
   - boiling point distribution (as described in Subsection 3.3.1),

- compounds of regulatory interest, and
- O_2/CO_2 (optional);

6. Open inlet and outlet valves and start airflow through the column at a constant flow rate of 0.04 L/min (0.0014 ft^3/min) (for sampling purposes it is more convenient to apply a pressure upstream). If it is desired to distinguish between aerobic biodegradation and volatilization, then N_2 sweep gas may be used instead of air with some columns. In most cases, it is desirable to pass the inlet air/vapor stream through a bubbler to humidify the air and prevent moisture loss during the test. If aerobic biodegradation experiments are to be conducted, CO_2-free air should be utilized at the sweep gas;
7. Monitor total contaminant concentration continuously (or as often as possible) in the effluent vapor stream C_{vapor} (mg/L). It is important that an appropriate analyzer be used, such as a flame ionization detector (FID) for most hydrocarbons. Based on this data and measured flow rates Q (L/min), compute continuously the total hydrocarbon mass lost by volatilization $M_{lost}(t)$ (mg) as time t according to the expression:

$$M_{lost}(t) = \int_{t=0}^{t} QC_{vapor}dt \approx \sum_{i=1}^{n} \frac{1}{2}(QC_{vapor}(t_i - \Delta t_i) + QC_{vapor}(t_i))\Delta t_i \quad [3.47]$$

For biodegradation tests, one can use the CO_2 effluent data or O_2 consumption data to estimate mass losses;

8. When data indicates that 50%, 75%, 90%, and 95% of the total initial hydrocarbon mass has been lost by volatilization ($M_{lost}/M_{HC}(t = 0)$ = 0.5, 0.75, 0.90, and 0.95), then sacrifice a column and perform the analyses specified under item 3 of the protocol. The fifth column should be used as a duplicate of one of these (most often the end of the test);
9. Effluent vapor samples should be collected and analyzed as described under item 5 whenever the effluent vapor concentration (as measured by the on-line total hydrocarbon analyzer) decreases by 50% from the concentration of the previous analysis; and

10. In addition to the chemical analysis and flow rate data collection, the pressure drop across the column and temperature in the column should be monitored.

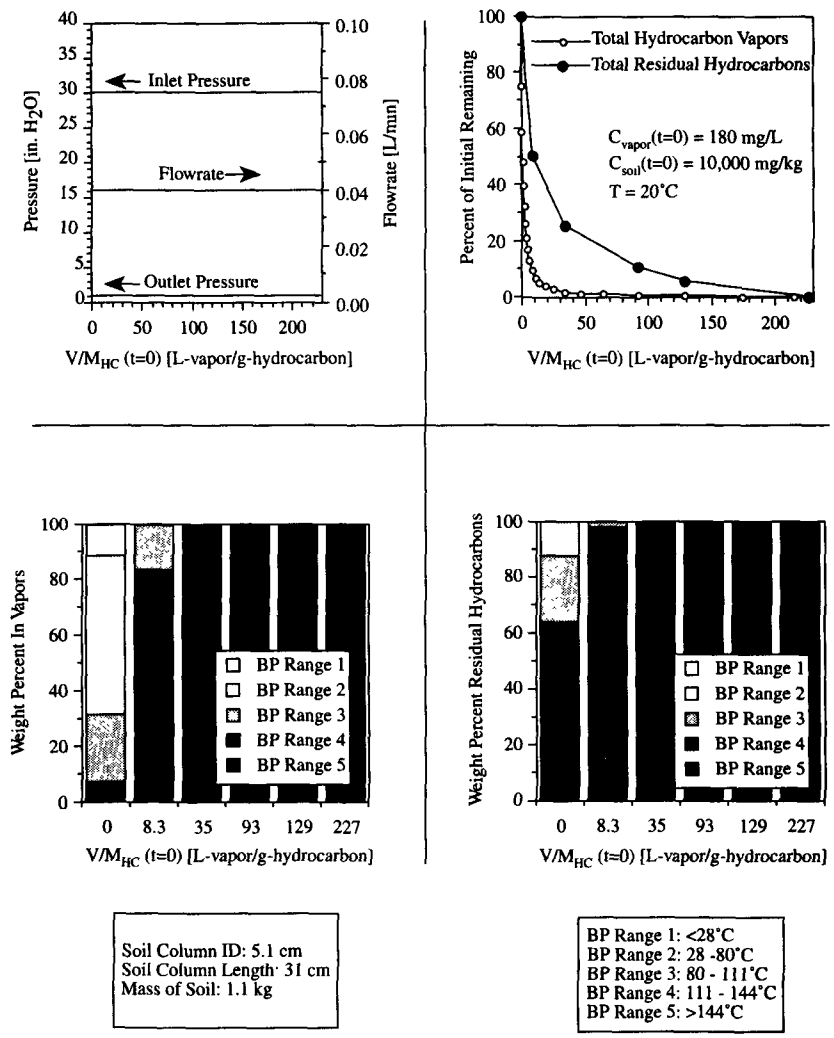
Data from the test should be reduced and displayed as shown in figure 3.26 (on page 3.73). If biodegradation is to be studied, plots showing effluent CO_2 and O_2 vapor concentrations as a function of time should also be constructed. Note that all measurements are being presented as a function of the volume of sweep gas passed through the column, normalized to the initial mass of contaminant. This normalization approach may not be appropriate for biodegradation studies. If the flow rate is held constant during the test, this is equivalent to $Qt/M_{HC}(t = 0)$. This is the proper way of reducing the data for a volatilization-dominated process as suggested by theory presented in Section 3.2. It is also common to see data presented as a function of the volume of sweep gas passed through the column normalized to the volume of vapor in one vapor-filled "pore volume" in the column; however, this normalized dependence on pore volumes is appropriate only when the partitioning of contaminants into the vapor phase is linearly proportional to the concentration of contaminants in the soil matrix or when the samples have been obtained from a uniformly-contaminated site. Use of these data in the system design process will be demonstrated in Section 3.4.

3.3.4 Field Pilot-Scale Activities

Field pilot-scale activities, items 4 through 10 of table 3.3 (on page 3.59), are focused upon the in situ measurement of soil permeability to vapor flow, zone of vapor extraction, extracted gas concentration and composition, aerobic biodegradation rates, and flow balancing requirements (for injection/extraction systems). Regardless of the level of complexity, all activities require a minimum test system consisting of the following:

- test vapor extraction well;
- test air injection well (if air sparging is being evaluated);
- vacuum pump and/or blower to induce air flow;
- vapor treatment system (if required);
- calibrated flow meter(s); and
- calibrated pressure/vacuum gauge(s).

Figure 3.26
Hypothetical Laboratory Soil Column Test Results



Soil Column ID: 5.1 cm
Soil Column Length: 31 cm
Mass of Soil: 1.1 kg

BP Range 1: <28°C
BP Range 2: 28 -80°C
BP Range 3: 80 - 111°C
BP Range 4: 111 - 144°C
BP Range 5: >144°C

Depending on the information desired, additional characterization activities may also require the following:

- sampling ports in the process lines;
- in situ monitoring installations (for both vadose and saturated zones);
- sampling devices (sampling pumps, syringes, etc.);
- analytical instruments (hydrocarbon analyzer, gas chromatograph, etc.);
- tracer gas delivery system; and
- tracer gas monitoring system.

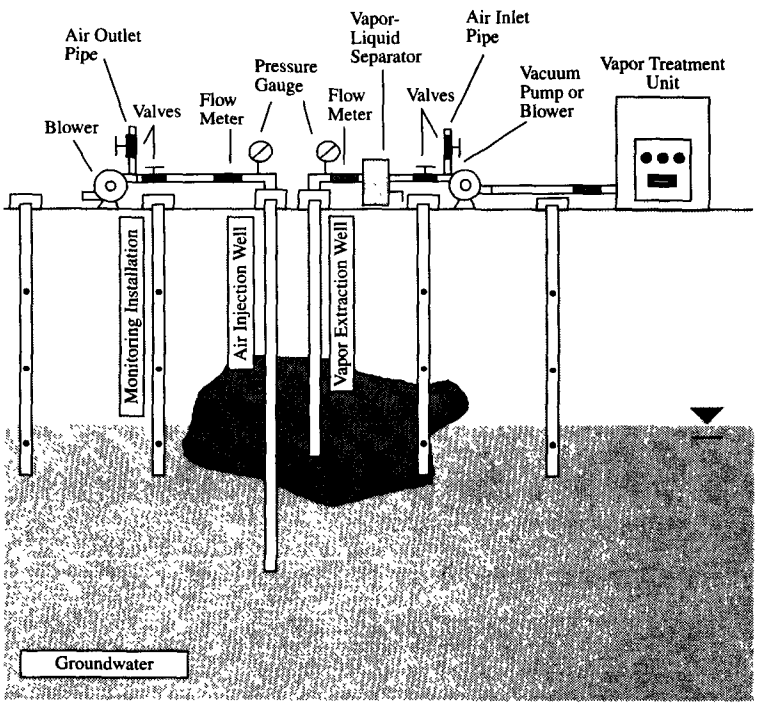
The goal and requirements of each of the activities listed in table 3.3 (on page 3.59) are discussed in more detail below. It is useful at this point, however, to discuss the proper installation of the "minimum test system," since this is a central feature of all the activities.

As a first consideration, pilot vapor extraction and air injection test wells should be placed within the area to be treated by a full-scale system. This typically means that extraction wells are placed within the contaminated soil zone and screened intervals are selected so as to induce air flow through or past (in the case of highly heterogeneous media) the zone containing contaminants. For some bioventing scenarios discussed in Subsection 3.1.3, test wells may actually be placed outside the zone containing contaminants. The installation of injection wells should be based on similar considerations. Air injection wells used for air sparging are typically installed where residual contamination is suspected and care must be taken to screen the wells in a narrow interval (0.3 to 1.0 m (1 to 3.3 ft)) below the suspected depth of impacted soils. At sites where a number of distinct zones are to be treated and a full-scale system is likely to include wells screened in each zone, more than one test well is appropriate. In practice, existing groundwater monitoring wells are often used for pilot-scale testing; however, the reader is cautioned that this is appropriate only in cases where the capillary fringe area is the zone of interest. Otherwise, pilot-tests conducted with these wells may not be representative of actual full-scale operation.

Care should be taken in connecting test wells, flow meters, pressure gauges, and blowers or vacuum pumps at the manifold. Since most blow-

ers/vacuum pumps are driven by fixed-speed motors, extraction/injection flow rates are often controlled by installing gate/block/globe valves and an air inlet/outlet pipe on the manifold as shown in figure 3.27. Although a single in-line valve is sufficient to control the injection/extraction flow rates, the air inlet/outlet pipe is typically included to allow the same level of control, while also preventing blower/pump overheating. It is very important to insure that flow meters and pressure/vacuum gauges are placed between the wellhead and first encountered valve or piping junction, otherwise the flow rate and applied pressure/vacuum at the wellhead cannot be measured accurately. Unfortunately, this is not always done in practice,

Figure 3.27
Simplified Field Pilot Test Schematic for Vapor Extraction-Based Technologies



and these measuring devices are often found incorrectly located between the blower/vacuum pump and an air inlet/outlet valve.

3.3.4.1 Vapor Flow vs. Applied Vacuum/Pressure Test

In order to select an appropriate vapor extraction blower/vacuum pump, it is necessary to measure extraction flow rates as a function of applied vacuum for each test well. For a pilot-test system connected as shown in figure 3.27, this is accomplished through 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 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;
6. In a series of increments, slowly close the air inlet valve until fully closed; and
7. For each increment, allow the flow rate to stabilize and record the wellhead vacuum and flow rate.

For systems using air injection, an air injection test is conducted by a procedure similar to the extraction test described above. The recommended sequence is:

1. Open air outlet valve;
2. Close the valve leading to the wellhead;
3. Turn on the blower so that air is being forced out only through the air outlet line;
4. Open fully the valve leading to the wellhead;
5. Once the flow rate (if any) has stabilized, record the wellhead pressure and flow rate;
6. In a series of increments, slowly close the air inlet valve until fully closed; and

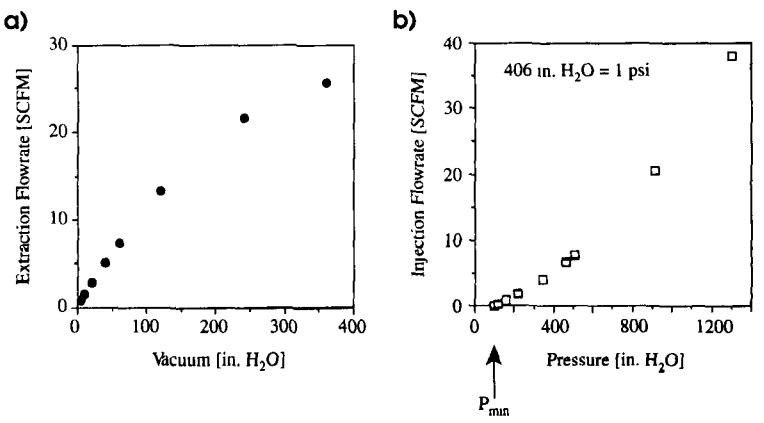
7. For each increment, allow the flow rate to stabilize and record the wellhead pressure and flow rate. In air injection for air-sparging systems, no flow will be measured until the minimum pressure required to initiate flow is exceeded. Record the pressure at which flow is first initiated.

If these are the only data desired, the injection/extraction test can usually be conducted within a few hours, since flow rates typically stabilize (for all practical purposes) within a few minutes. Data from these tests should be presented as shown in figure 3.28. These are recommended methods only and there are other acceptable methods of displaying the data. Flow rates should be reported in "standard" flow rate units (the equivalent volumetric flow at 1 atm pressure); if Q is the flow rate measured at an absolute pressure P, then the standard flow rate $Q^* = Q(P/1\ \text{atm})$.

3.3.4.2 Extracted Vapor Characterization vs. Time

Whether evaluating soil vapor extraction, air sparging, bioventing, or any other variation of vapor extraction technology, there is a need to determine the extraction-vapor concentrations and compositions that are likely to be observed. This information, along with knowledge of possible extraction

Figure 3.28
Presentation of (a) Extraction and (b) Injection Test Data



well flow rates and regulatory requirements, is used to determine what process modifications (vapor treatment units or lower flow rates) are necessary to comply with emissions requirements.

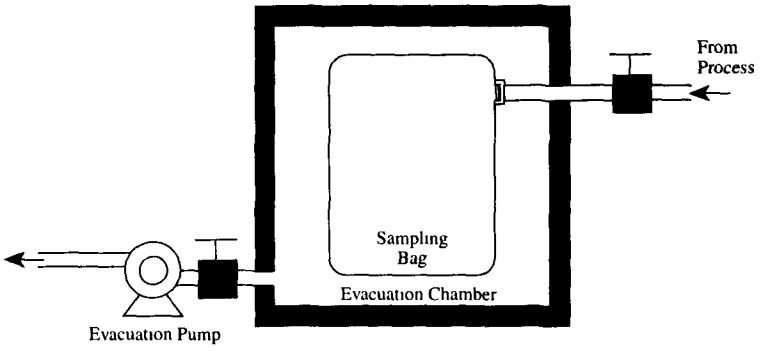
The opportunity to obtain this information is presented during the extraction/injection test described above in Subsection 3.3.4.1. Total vapor concentrations can be measured as a function of time with an on-line total hydrocarbon analyzer (flame-ionization detectors are recommended for most hydrocarbons), and vapor samples can be collected and subjected to gas chromatographic analyses. Although the collection and analyses of these samples is not a complicated process, the following measures should be incorporated into any sampling plan:

1. Samples should be collected between the extraction wellhead and any air inlet line; and
2. The test should to be conducted for a long enough period to assure that vapor concentrations are representative of extended system operation; the test should be conducted long enough to extract several (probably >5) pore volumes of soil gas.

The first measure assures that representative samples of the extracted vapors are obtained. Care should be taken to assure that sampling ports are not placed within a few feet of any air inlet junction, as significant backmixing may occur near the junction. One must also recognize that the vapor samples are being withdrawn from a system under vacuum and this warrants special care. The recommended sampling procedure is to draw the sample through on-line analyzers or into sampling bags without having it pass through a pump. This is easier to do with an on-line analyzer, as a sampling pump can usually be installed downstream of the detector. Obtaining bag samples requires a little more creativity. It is usually accomplished as shown in figure 3.29 (on page 3.79). The sampling bag is connected to a port within a chamber that can be sealed and evacuated. The exterior port is then connected to the process sampling location and by evacuating the sealed chamber, a sample is drawn into the sampling bag without having passed through a sampling pump.

The second measure listed above is important because samples obtained at the start of a vapor extraction pilot test are not representative of sustained system operation. When flow is initiated in a pilot test, one typically observes relatively high extracted vapor concentrations that decrease rapidly

Figure 3.29
Schematic of Sampling Apparatus Used When Sampling Vapors Under Vacuum Conditions



over a period of a few hours to a few days to some more stable level (at least, the rate of decline in concentration is much slower than observed in the initial start-up period). This is because the initiation of subsurface vapor flow draws vapors from the contaminant source as well as from other areas to which contaminant vapors have migrated from the source over time. Until these vapors are recovered by the extraction well, the measured extracted vapor concentration is elevated above levels that will be observed during more sustained operation of the system. Consequently, it is useful to estimate how long a given test must be conducted. Here the approach used by Johnson and Stabenau (1991) is followed, which approximates this transient period $\tau_{start\text{-}up}$ (s) as the time required to sweep one "pore volume" of vapors through the flow zone:

$$\tau_{start-up}(t) = \frac{\varepsilon_A \pi R_F^2 H_F}{Q_{well}} \qquad [3.48]$$

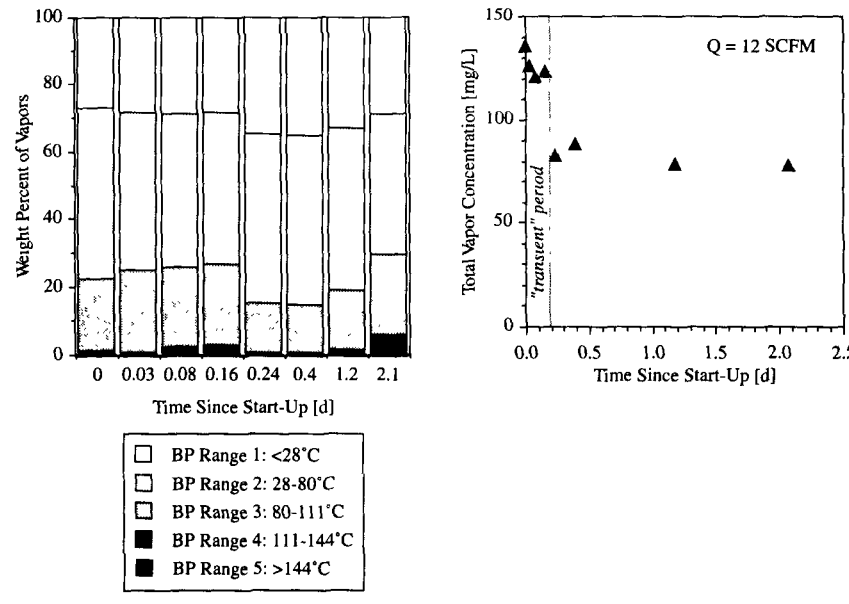
where ε_A denotes the air-filled void fraction in the subsurface (0.30 is a good approximate value), Q_{well} (cm^3/s) represents the volumetric flow rate to the extraction well, and the flow zone has been approximated by a cylinder

of radius R_F (cm) and height H_F (cm). In the absence of any other information, R_F can be estimated to be roughly equal to the depth to top-of-screen for the well (H_F). For an extraction well screened from 3 to 4 m (10 to 13 ft) BGS pulling 0.01 m^3/s (≈20 standard ft^3/min), equation [3.48] predicts the transient period to last approximately 45 minutes. Data collected during this test should be reduced and displayed as shown in figure 3.30.

3.3.4.3 Subsurface Vapor-Phase Pressure Distribution

When subsurface monitoring installations are available, the subsurface vapor-phase pressure distribution resulting from injection/extraction tests can also be monitored. This information is used to assess the zone of con-

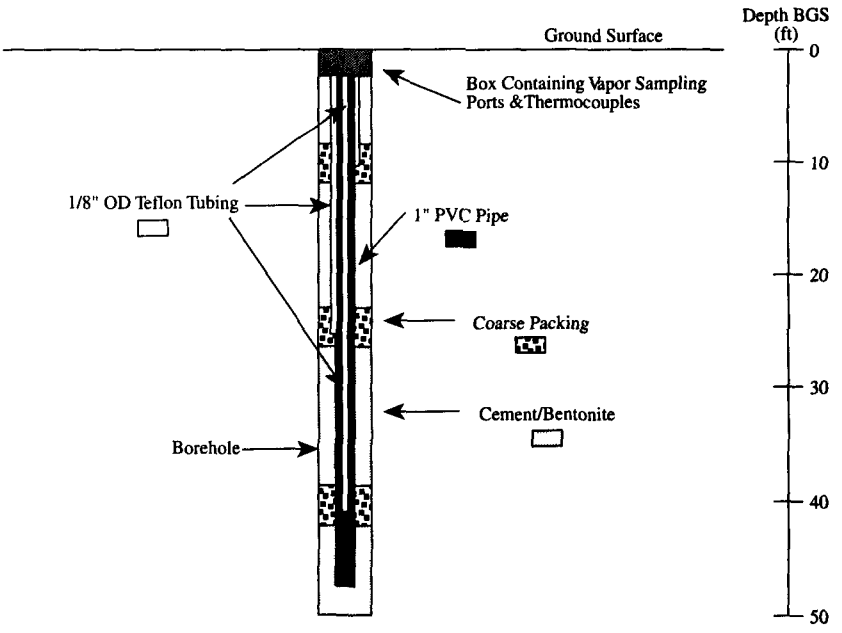
Figure 3.30
Presentation of Extracted Vapor Analyses from Pilot Test



Adapted from Johnson, P.C., Stanley, C.C., Byers, D.L., Benson, D.A., Acton, M.A., Soil Venting at a California Site: Field Data Reconciled with Theory, 274-275, in Hydrocarbon Contaminated Soils and Groundwater, Vol. 1, Kostecki, P.T., Calabrese, E.J., Eds., Lewis Publishers (subsidiary of CRC Press), Boca Raton, Florida, 1991. With Permission.

tainment and can be used also with permeability distribution data and flow modeling to gain a better understanding of the subsurface vapor-flow patterns. These pressure monitoring installations may simply consist of soil-gas probes driven into the subsurface, or they may be dedicated installations that have been installed in soil borings during the hydrocarbon/geologic assessment phase of site characterization. Care should be taken in the interpretation of data collected from driven soil-gas points as leakage or short-circuiting is a risk. This is particularly true of shallow (less than 1 to 2 m (3 to 6.5 ft)) driven points. See figure 3.31 which presents an example installation. Based on the theoretical analysis presented in Subsection 3.2.4, it is recommended that monitoring points be placed relatively close (1, 3, 7, 15

Figure 3.31
Vadose Zone Monitoring Installation



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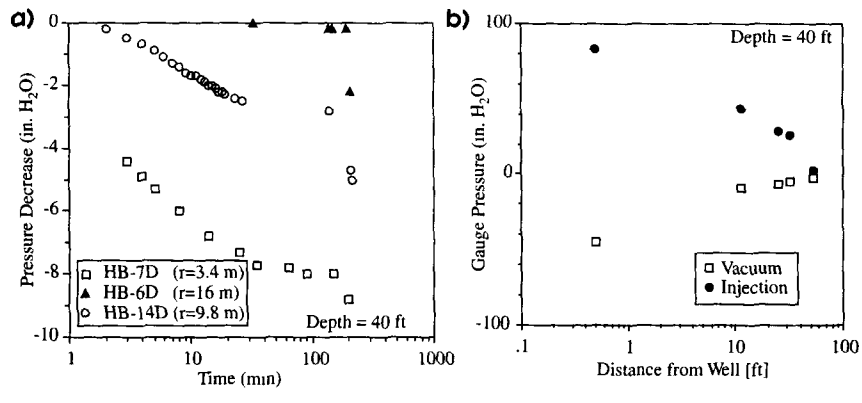
m (3.2, 10, 23, 49.2 ft)) to the test injection/extraction well, since the vapor-phase subsurface pressure dissipates rapidly with distance from the injection/ extraction point.

The extraction/injection tests described in Subsection 3.3.4.1 present the opportunity for measuring transient pressure changes and steady-state pressure distributions for each change in extraction/injection vapor-flow rate. Transient data can be used as an alternate means of obtaining soil permeability data, as explained in Subsection 3.2.5. The steady-state data are used to define the zone of vapor containment and may be used with permeability distribution data and flow modeling to gain a better understanding of the subsurface vapor-flow patterns. It may not be practicable to collect transient data in very permeable soils (medium to coarse sands), as the flow field is established within a very short period.

Transient data are often presented, as shown in figure 3.32a, in accordance with the theory presented in Subsection 3.2.5. The presentation of steady-state data varies, depending on the density of sampling points. For sparse data, the presentation is usually similar to that of figure 3.32b, as

Figure 3.32
Presentation of Subsurface Pressure Monitoring Results from Pilot Test
a) Transient Results b) Steady-State Results



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suggested by the theory presented in Subsection 3.2.5. More extensive data permit presentation of interpolated contour plots superimposed on the geologic cross-sections.

3.3.4.4 Subsurface Vapor Concentration Distribution and In Situ Respirometry

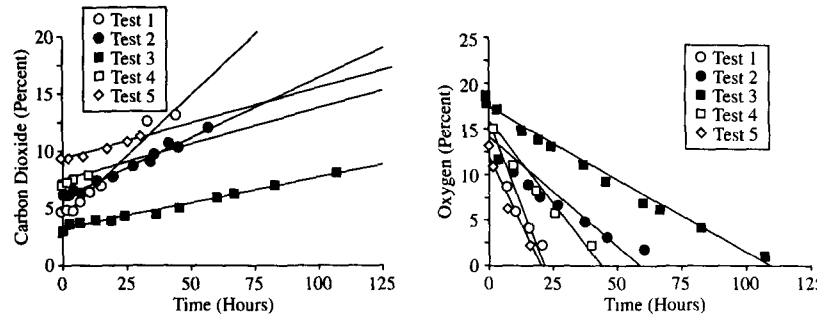
Subsurface monitoring installations used for vapor-phase pressure monitoring can also be used to collect soil-gas samples before and during a pilot test. Procedures discussed in Subsection 3.3.4.2 for collecting vapor samples under vacuum conditions should be followed.

The relative impact of bypassing (air flows to extraction well without passing through the zone of contamination) and mass-transfer limitations on vapor extraction-based system performance can be assessed by comparing soil-gas concentrations with levels measured in extraction wells. Typically, measured soil-gas concentrations in the contaminant-impacted zone are greater than concentrations measured in extraction well soil gas (as this represents an average concentration of all vapors reaching the well), and the difference between the two gives a qualitative indication of the degree to which flow is being induced through the contaminant zone. In addition, the measurements can be used as supporting evidence in defining the zone of vapor flow; once the transient period (discussed in Subsection 3.3.4.2) is over, a reduction in soil-gas concentrations is typically observed in areas in which flow has been induced.

These measurements play a significant role in the pilot testing of air-sparging (or any other air injection) systems, as they can quickly indicate if there is uncontrolled pressure-driven migration of vapors away from the source area. When this migration occurs, monitoring locations are installed between the zone of treatment and any sensitive receptors (basements, etc.).

In situ soil-gas measurements are used also to assess aerobic contaminant degradation rates. In an "in situ respirometry test," the extraction/injection flows are stopped and the disappearance of O_2 and appearance of CO_2 are monitored with time. It is important that this test also be conducted in a "background" area in order to assess the "natural" subsurface respiration rate. The background area ideally is similar with regards to geological and microbial conditions and differs only in that no contaminant is present. See figure 3.33 (on page 3.84) for data resulting from a test. Interpretation of these data are discussed in Subsection 3.5.3.3.

Figure 3.33
Oxygen Utilization and Carbon Dioxide Production in Various Phases of a Bioventing Project at Tyndall AFB, Florida



Source: Miller 1990

3.3.4.5 Groundwater Elevation Changes

During a vapor extraction pilot test, it is important to monitor groundwater elevation changes where contaminants are distributed throughout soils located in close proximity to the water table. Subsurface vapor-phase pressure changes caused by inducing flow affect the groundwater elevation. An applied vacuum of "X" in. H_2O will cause a steady-state rise in the water table of "X" in. (similarly, positive pressures resulting from injection can cause water table depression). Monitoring these elevation changes is important, as they can limit the range of vacuums that may be applied without pulling water up the pipe or saturating the contaminant zone or they may indicate that a groundwater drawdown system is necessary.

Groundwater elevation changes during air-sparging tests are taken as indications of airflow in the saturated zone by some practitioners. Temporary groundwater mounding has been observed in close proximity to air-sparging wells.

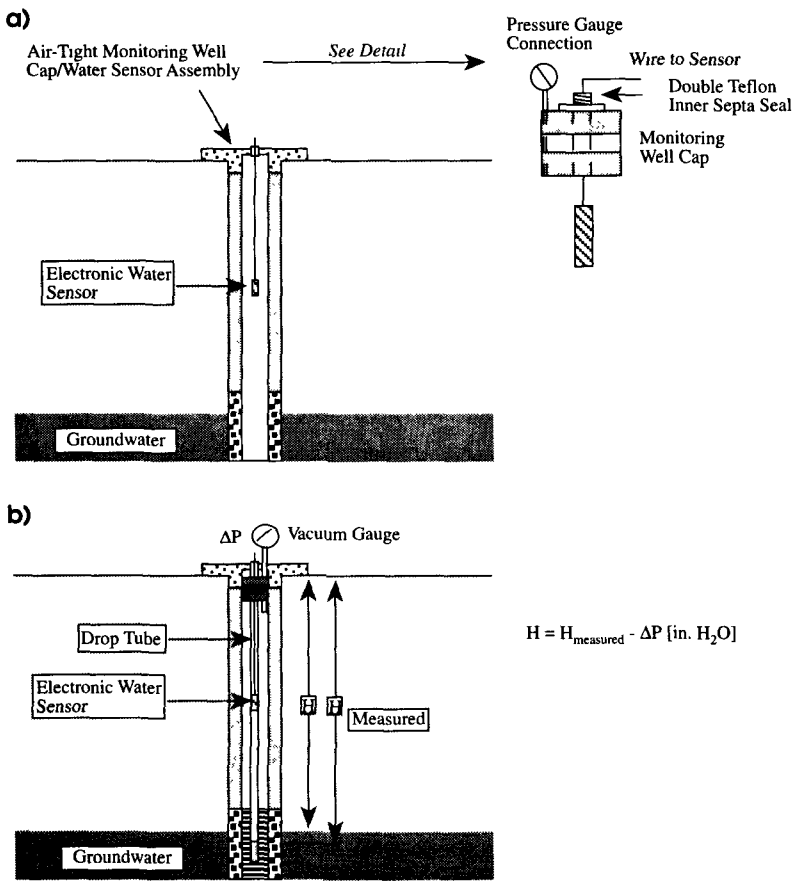
Monitoring of elevation changes is important and care must be taken in selecting a method that does not involve changing the subsurface pressure distribution, as when a monitoring well cap is opened. There are a number of practical methods for taking these measurements involving the use of dip tubes, pressure transducers, and interface probes. See figure 3.34for illus-

tration of two possible approaches. See figure 3.35 (on page 3.86) for data resulting from a pilot test.

3.3.4.6 Groundwater Monitoring

Groundwater monitoring can also be conducted during field-pilot tests and samples obtained from monitoring wells or piezometers can be ana-

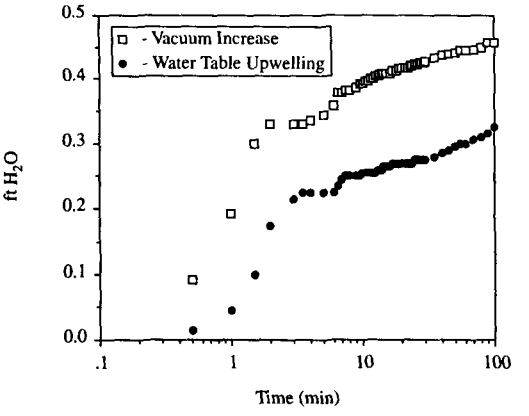
Figure 3.34
Groundwater Elevation Monitoring Approaches: a) Direct Measurement b) Indirect Measurement



lyzed for dissolved contaminants and dissolved oxygen. With soil vapor extraction standing alone, the information resulting from a short-term test may not be very revealing. In air sparging, however, it is possible that significant changes in some indicator parameters might be observed during a short-term test.

It is important to recognize that groundwater samples obtained during air sparging may, or may not, be representative of aquifer conditions. Because of formation stratification and other subsurface heterogeneities, air channels that propagate outward from the injection point may intersect a monitoring well and short-circuit to the vadose zone through the well casing or borehole annulus. If this occurs, analysis of groundwater monitoring samples will generally reflect higher dissolved oxygen and lower contaminant levels than those that exist in the aquifer. Use of multiple, nested piezometers will help eliminate this potential confusion. See figure 3.36 (on page 3.87) for sample data from an extended air-sparging pilot test.

Figure 3.35
Measured Water Table Upwelling



[ft H_2O] denote vacuums expressed as equivalent water column heights

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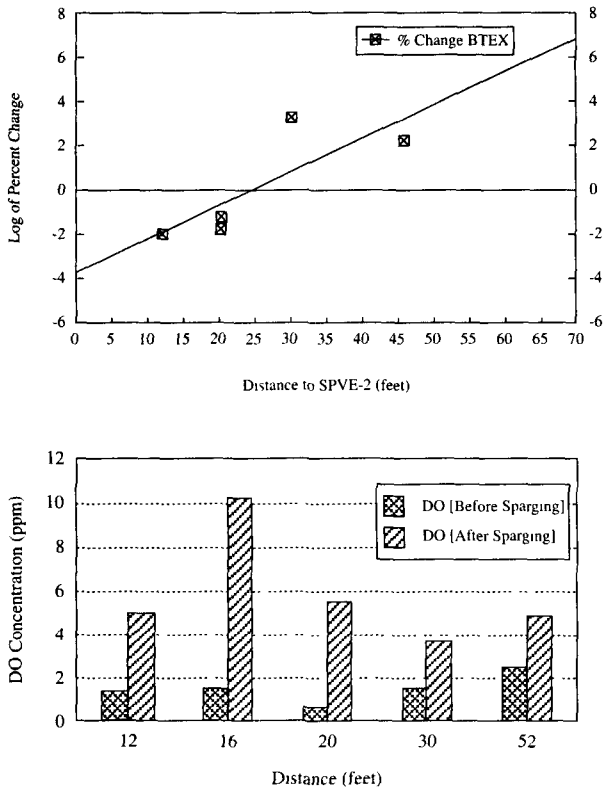
Figure 3.36
Groundwater Monitoring Results During Application of Air Sparging



Source: Felten et al 1992

Test Date 3/18/92

3.3.4.7 Tracer-Gas Tests

The use of tracer-gas tests is probably the most straightforward and definitive way to assure containment of injected vapor streams during air sparging or during other processes that utilize air injection. They can also be used to better define the flow field.

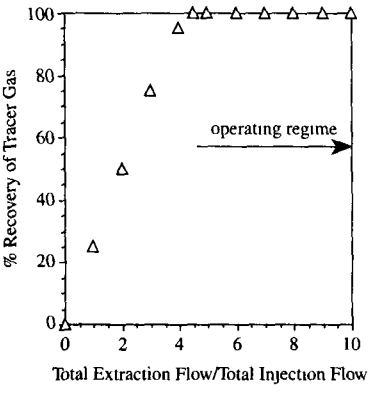
In a tracer-gas test, an inert, easily-detectable tracer gas is fed into the injection vapor stream or into a subsurface location. Its rate of recovery in the extraction system and in soil-gas samples is then monitored to assess ability to control the vapor-flow field. Injection and extraction flow rates can be tuned to assure containment of the vapor-flow field as recovery efficiency is monitored and analysis of soil-gas samples permits a better picture of vapor-flow paths to be developed. Transient analyses can also be used to gain a better understanding of travel times or vapor velocities.

Two tracer gases frequently used in environmental applications are SF_6 and He. See figure 3.37 for sample data resulting from an extraction/injection test.

3.4 System Design

The goal in designing vapor extraction-based processes is to specify system components and operating conditions that will meet remedial goals (i.e., cleanup levels and specified duration), while operating within constraints (i.e., costs, emissions limits, etc.). Unfortunately, because of the

Figure 3.37
Presentation of Tracer Test Results



compounding of uncertainties and inherent limitations arising from natural heterogeneities, site characterization data, and predictive capabilities, even well-reasoned goals cannot realistically be expected to be met with a high degree of confidence. Consequently, the design of vapor extraction-based processes continues even after the initial system is installed and started. System performance must be monitored, the results interpreted, and system modifications made accordingly. Of all the information contained in this section, the most important message for the reader is that *all systems should be of robust design and flexible so as to handle a wide range of system expansions and operating conditions.* The additional cost incurred in building-in adequate flexibility is usually small compared to total project costs and this incremental investment will often provide long-term savings.

As with the presentation of characterization activities (Section 3.3), the intent here is not to prescribe a standard system design process. Instead, a range of possible design approaches that encompass most current practices, as well as suggested improvements, is presented. For each approach presented, data requirements are specified and the advantages and disadvantages of that approach are discussed. The design approaches, summarized in table 3.5 (on page 3.90), are discussed in the order of complexity and expertise required.

The system design process should not be initiated until a feasibility evaluation has been made. In making a feasibility evaluation, however, aside from employing the very general tables, graphs, or guidelines available, one of the best methods (but at many sites not cost-effective) is to design a system and then assess its implementability. An example of this approach, which is a variation of that initially presented by Johnson et al. (1990, 1991), is presented in Chapter 4.0. Experience teaches that some of the most simplistic design practices are actually more valuable for estimating feasibility than for designing systems.

Along with the operating conditions, the following components are typically specified in a soil vapor extraction-based system design:

- number of vapor extraction wells;
- number of air injection wells;
- well location(s);
- well construction(s) (depth, screened interval, materials, etc.);

Table 3.5
Soil Vapor Extraction-Based Processes Design Approaches

Approach	Required Information[1]	Advantages	Disadvantages
• empirical approach	• 1, 2	• quick, easy, low skill level required	• unknown system performance, technology may not even be applicable
• minimization of capital expenses	• 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 approaches	• 1, 2, 4, 5[2], 6	• insures containment of hydrocarbon vapors	• unknown system performance, does not insure remediation in reasonable time frame
• screening level model-based approaches	• 1, 2, 3[2], 4, 5, 6, economic data	• little effort required, design based on desired performance, cost of analyses not prohibitive	• requires higher level of expertise & ability to interpret data
• detailed numerical modeling and optimization-based approaches	• 1, 2, 3, 4, 5, 6, 7, 8, 9, economic data	• design can be optimized & based on desired performance	• requires highest level of expertise & ability to interpret data, cost may be prohibitive

1 - refers to activities defined in table 3 3
2 - optional, not always used in this approach

- extraction blower(s) or vacuum pump(s);
- injection blower(s);
- vapor treatment unit(s);
- equipment manifolding & piping; and
- instrumentation and controls (flow meters, sampling ports, vapor concentration monitoring, control valves, pressure or vacuum relief valves, etc.).

The method for prescribing each component under the various design approaches is discussed in the subsections immediately following. With the exception of the number of wells selected, well locations, and the operating conditions, strategies for determining the design parameters are relatively

similar for all approaches. To avoid repetition, the methods for prescribing the common system components are discussed first.

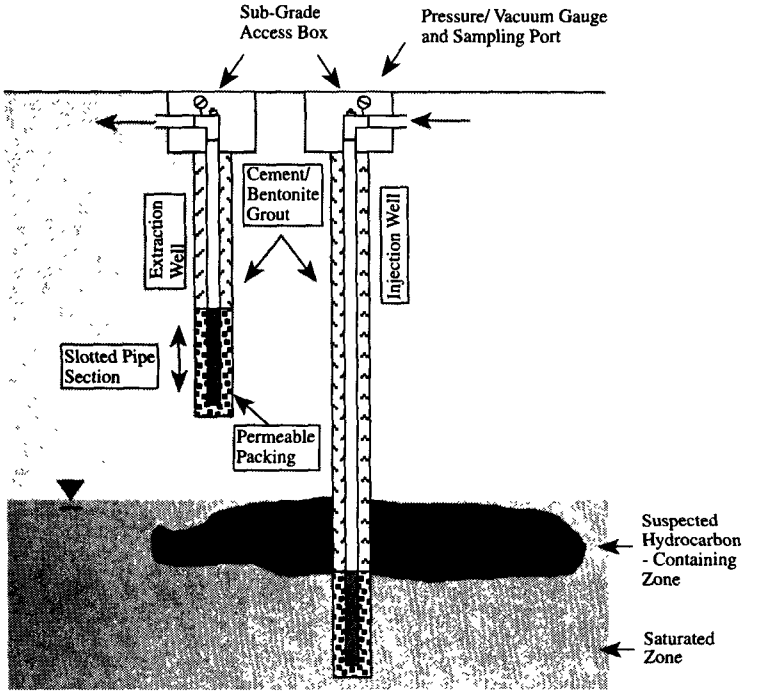
3.4.1 Extraction/Injection Well Construction

For the most part, vapor extraction-based processes have predominantly employed vertical wells as a means of directing the flow of vapors. In light of recent advances in horizontal drilling techniques, however, the use of horizontal wells is being explored, as these offer some unique advantages (vapor extraction beneath buildings, greater effective airflow per well in a narrow depth interval). In addition, vapor extraction trenches have been used for shallow groundwater sites. Despite the obvious physical differences in each of these scenarios, the following factors must be addressed when specifying well construction. These are:

- size of conduit (pipe);
- conduit material;
- length of interval perforated or "screened" to vapor flow;
- the packing and screened-interval specifics;
- method of well installation in the subsurface; and
- minimization of vapor flow "short circuiting."

Well diameters ranging from 1 to 6 in. are commonly employed in extraction/injection well construction. Smaller diameter wells present an advantage in that they may be driven to depths of about 9 m (30 ft) if the site geology is amenable; however, the drawback is that there may be significant line pressure drops when high vapor flow rates are required. See Peters and Timmerhaus (1980) for estimation of pressure drops due to flow in pipes. Larger diameter wells are almost always installed by first drilling a borehole and then placing the well casing within. A permeable (less resistant to vapor flow than the surrounding formation) packing material is placed in the annulus around the screened interval, and the remaining annular region is then grouted (using cement-bentonite grout) to prohibit short-circuiting of the airflow. An example of this kind of construction is shown in figure 3.38 (on page 3.92). For most applications PVC piping is adequate; however, other materials should be used in high-pressure, high-temperature scenarios, or extremely adverse environmental conditions. As to systems using air injection wells, it is important to recognize that air

Figure 3.38
Schematic of Standard Extraction/Injection Wells



passing through an injection blower may undergo a significant temperature rise (especially for high-injection pressures). In this case, the practitioner should consider the use of injection well materials capable of withstanding high-temperature conditions.

Screened interval locations should be chosen to maximize airflow through the desired zone. In the absence of accessible predictive tools, the practitioner must develop a good intuitive feel for subsurface vapor-flow paths and the influence of geologic conditions and man-made obstructions and conduits. In vapor extraction systems, the screened interval is usually set across the hydrocarbon impacted zone, unless it extends to ground sur-

face, or over a very wide interval (e.g., 15 to 30 m (50 to 100 ft)). In this case, nested wells are often used to better control vapor flow through the entire zone of contamination. In air-sparging injection wells, the top of the screened interval must be set below the water table and the zone of residual contamination; the screened interval itself is typically short (0.5 to 1.0 m (1.6 to 3.3 ft)), and is often placed not much below the contaminant-impacted zone, as there are concerns about the ability to control the air-flow pathways, even though in cases of two contaminant zones this may lead to limited zones of influence.

Screen size should be selected to maximize the area open for vapor flow, while maintaining an open conduit. Packing materials should be at least as permeable to vapor flow as the formation itself.

3.4.2 Vapor Treatment

Vapor treatment units are selected to allow the operator to meet regulatory requirements, which often take the form of (1) a prescribed percent reduction in contaminant concentrations across the treatment unit (e.g., 95% reduction in total contaminant concentration), (2) a required limit on emission rate of specific or total hydrocarbons (e.g., 0.45 kg/day (1 lb/day) total hydrocarbon emission restriction), or (3) some combination of the two. In some areas it is permissible to discharge untreated vapors, if dispersion modeling results indicate adequate concentration reduction within a given distance of the source stack.

A variety of units meeting most needs are currently offered by vendors for lease or purchase. Most fall under one of the following categories:

- thermal oxidation - vapors are destroyed by combusting them in a chamber that is designed to maintain a temperature of >930°C (1,700°F) and a gas residence time of about one second. Supplementary fuel is required when influent contaminant concentrations drop below explosive levels. Many geometries are available, ranging from units that look like rectangular boxes to others that resemble flare stacks. Thermal oxidizer units are the most robust in terms of being able to handle a wide range of vapor concentrations and are often more reliable (from an equipment standpoint) than other kinds of units; however, operating

expenses for supplemental fuel can become prohibitive at lower vapor concentrations;

- internal combustion engines - in one of the more novel approaches to vapor treatment, extraction wells are connected to the intake manifold of an internal combustion engine, which then serves as the extraction pump as well as the vapor treatment device. The vapors fuel the engine; supplemental fuel is added if the vapor concentration is too low. Concerns with noise, maintenance, and supplemental fuel costs limited the use of early versions of these units; however, recent advances in the design have led to the development of versatile and easily transportable units;
- catalytic oxidation - vapors are passed through a catalyst bed maintained at an elevated temperature (often 260° to 370°C (500° to 700°F)), where they are combusted. Careful control of the temperature is essential to prevent melt-down of the catalyst. These units are efficient processors of lower vapor concentration streams (<1% v/v); higher concentration streams must be diluted with air. (See the monograph in this series, *Innovative Site Remediation Technology: THERMAL DESTRUCTION*, for a more extensive discussion of catalytic oxidation.);
- adsorption units - contaminant vapors are adsorbed out of the flowing-gas stream onto a support material, such as vapor-phase activated carbon or zeolite beds. Typically, these units do not have large capacities and must be run in a recycle mode when contaminants are to be desorbed (e.g., by steam stripping) when the capacity has been exceeded. These units are not used as extensively as those described above, but they do have the advantage of being able to recover contaminants, rather than merely destroying them. In addition to solid adsorption materials, relatively nonvolatile liquid hydrocarbons may also be used to adsorb volatile compounds from vapor streams; and
- biological processes - biologically-based units are currently in the development and evaluation phase. Vapors are transferred to a bacteria-containing media (e.g., liquid in a fluidized biological reactor or soil/peat in a "biofilter") where contaminant-degrading bacteria convert them to carbon dioxide and water. (See

monograph in this series, *Innovative Site Remediation Technology: BIOREMEDIATION*, for a more extensive discussion of biological processes.)

When selecting a vapor treatment unit it is necessary to specify the range of influent vapor concentrations, range of total vapor flow rates to be processed, and treatment requirements. At this point, the user should select the most cost-effective option, or combinations of technologies. Some indication of the applicability of a number of options has been given in the preceding text. Purchase prices for many off-the-shelf units (appropriate for flows <235 L/sec (500 standard ft^3/min)) currently range from $40,000 to $150,000. Some care should be taken in selecting a vapor treatment strategy, as this often limits the range of potential operating conditions. In many cases, the incremental cost for larger capacity units (e.g., cost differential between a 47 and 95 L/sec (100 and 200 standard ft^3/min unit)) is not significant, and it is worthwhile investing the money to allow greater flexibility.

3.4.3 Extraction Pump/Blower and Injection Blower

In order to select extraction blowers, vacuum pumps, and injection blowers, the flow rate necessary at a given design vacuum or pressure is specified. This information is collected during the characterization activities outlined in Section 3.3. Based on these data, pump and blower manufacturers can specify which of these units is needed based on measured performance or "pump" curves for their equipment. Given a range of manufacturers and types of blowers and pumps, one generally chooses a unit based on cost, maintenance requirements, and experience with similar units. Since extraction and injection blowers and pumps are the heart of most above-ground vapor extraction equipment, it is recommended that most systems be designed with redundant blowers and pumps to allow for periodic failure and maintenance. Practitioners should also assess the need for explosion-proof equipment, as extracted vapor concentrations often exceed lower explosive limits.

Although lower cost blowers have historically been the predominant choice for vapor extraction, there is now a trend to install more versatile vacuum pumps, since the incremental cost for upgrading is usually not significant in relation to total remediation costs. Costs for units with capacities up to about 95 L/sec (200 standard ft^3/min) range from $1,000 to $10,000.

3.4.4 Instrumentation

Process monitoring is the focus of the discussion in Section 3.6; however, it is worthwhile to summarize here some of the instrumentation needs for any system design.

At a minimum, flow rates, applied vacuums or pressures, and extracted vapor concentrations should be monitored for each well, as well as for the total system. Except for total system flow and concentration measurements, sampling ports and measuring devices must be placed between extraction wellheads and the first downstream flow restriction or manifold junction; in injection wells, they are placed between injection wellheads and the first upstream flow restriction or manifold junction. If the system requires N extraction wells and M injection wells, at a minimum (N+M+1) flow meters and pressure/vacuum gauges and (N+1) vapor sampling ports are required. If tracer tests are to be conducted, (N+M+1) vapor sampling ports should be employed as well.

Total hydrocarbon measuring devices (e.g., continuous flame ionization detectors or explosimeters) are often placed in-line to assess changes in the total concentrations of contaminants in the extracted vapors. These are sometimes integral components of the vapor treatment unit.

In addition, there may be instrumentation associated with vapor treatment units, such as thermocouples, to measure catalyst bed temperatures. Many newer units are outfitted with a dial-in modem that provides notification of system shut-down.

3.4.5 Manifolds

The connecting of system components at the manifold has a significant effect on the operation and monitoring of vapor extraction-based processes; yet traditionally, little attention has been paid to this aspect of system design. As a first rule, the designer must allow for flexibility and future expansion. This means that the system design must easily accommodate the installation of additional wells, blowers, or vapor treatment units with minimal cost and disruption of an operating system. Valves must be installed to allow independent control of flow to and from each well, blower, and vapor treatment unit. Furthermore, the piping should be installed in a manner that facilitates replacement of equipment, especially blowers, pumps, and instrumentation.

Care should be taken to locate instrumentation where it can be readily monitored and replaced. Guidelines given above for the placement of flow meters, pressure gauges, and sampling ports should be followed.

3.4.6 Surface Seals and Passive Inlet Wells

The effect and usefulness of surface seals and passive air inlet wells in controlling vapor-flow paths are often debated among practitioners. Surface seals are touted as a means of expanding the radial influence of vapor extraction wells. Passive inlet wells supposedly allow better direction of the flow of air through a zone of contamination.

When employing vapor extraction wells and trenches at shallow depths (top of screened interval <3 m (10 ft) BGS) and in homogeneous soils, the user typically finds that the zone of influence of the well or trench does not extend much beyond a distance equivalent to the depth to top of the screen. The result is that a greater areal density of wells or trenches is required to assure vapor containment. In order to combat this problem, it has been suggested that sealing the ground surface might extend the vapor flow path and provide better control. Conceptually, this idea is acceptable and expectations are consistent with modeling results; however, before surface seals are installed at all sites, a determination should be made whether a "true" surface seal can be achieved in the field. It is unlikely, that a pneumatically effective surface seal can be achieved in the field by the methods typically proposed to prevent water infiltration (plastic liners and asphalt). A common assumption is that pavement and roads provide good pneumatic surface seals. Unfortunately, this may not be the case, since most roads and paved areas have cracks and joints that may act as air entry points, and they overlay an extremely permeable bedding material layer. In some cases, however, this bedding material is saturated (especially when adjacent to over-irrigated planters), and this limits the surface leakage of air. There have been reports[1] of surface covers employing composite soil:geomembrane sections with bedding layers compacted wet of optimum. These types of seals are specifically designed to prevent air infiltration and seem to achieve the theoretical effect of influencing air flow pathways. Methods such as these, however, are more substantial and involve more engineering

1. Hartley, James D. Personal Communication re McClellan AFB Operable Unit D Cover and Site S Soil Vapor Extraction System, February 28, 1995

than the most commonly proposed methods (single-layer plastic sheeting and asphalt).

Although ground surface covers cannot be automatically assumed to be effective surface air seals, they may still provide benefits by limiting water infiltration into the subsurface and reducing surface emissions of contaminants. In the latter case, contaminant vapors may collect in the permeable subgrade of an asphalt pavement but be limited in terms of surface flux by the small openings in the cracks or joints of the overlying pavement. System designs can incorporate surface seals with extraction ports to limit contaminant emissions to the atmosphere. Such surface seals, or vapor shrouds, are often integral components of the thermally-enhanced vapor extraction-based processes, discussed in Section 3.5.

The use of passive air inlet wells has been proposed where it is desirable to better direct the air-flow field. In concept, air is drawn into the subsurface through the passive air inlet well as a result of air being withdrawn from an extraction well. As with surface seals, however, there is little evidence showing any benefit in using passive air inlet wells. In the authors' view, based on field experience and theoretical considerations, such wells will significantly affect the flow field only if they are placed very close to the extraction well. This may be best understood by recalling that a rapid decline in vacuum with distance is typically observed within merely a few feet from a vapor extraction well. By placing a passive inlet well at a distance where the induced vacuum is normally small, the driving force for flow from that region is only incrementally changed.

3.4.7 Design Approaches

Approaches used in designing vapor extraction-based processes, listed in table 3.5 (on page 3.88), are discussed in the subsections immediately following. They are then compared in Subsection 3.4.8.

3.4.7.1 Empirical Approach

In the empirical approach, the most simplistic of the design approaches, the number of wells, well locations, and blower and vapor treatment requirements are specified based on previous experience, general guidelines, and intuition. The only essential information is a baseline geologic/hydrogeologic assessment summary indicating the general location of contaminant-impacted soils.

This design process can be easily and quickly performed. It requires a minimum level of skill in design and little understanding of vapor extraction-based processes. Unfortunately, performance of the resulting system may be problematic and may even cause detrimental effects (e.g., drawing vapors to sensitive receptors), just as can poorly-designed air-sparging systems.

In this design approach, the maximum system performance is limited by characteristics of individual system components. In addition, the practitioner risks purchasing and installing equipment that may not be appropriate.

3.4.7.2 Matching System Design to Existing Equipment

In this approach, the use of existing equipment is maximized in order to minimize capital expenses. In the extreme case, a vendor will merely connect a portable skid-mounted vapor extraction system to existing groundwater monitoring wells and then, the only installation cost is that of connecting the equipment.

Design data requirements are the same as those for the approach discussed in Subsection 3.4.7.1 and this approach suffers from the same drawbacks. But, of course, it does have the advantage of minimizing installation costs. Although these savings are likely to be offset by the increased operating costs of a very inefficient system, it is an approach often used in order to avoid the expense of customized systems. Drawbacks can be minimized by purchasing very robust equipment (e.g., vacuum pumps instead of blowers and large capacity vapor treatment units).

3.4.7.3 Radius-of-Influence Approaches

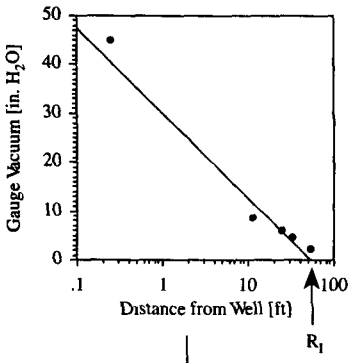
Radius-of-influence approaches are currently the most frequently used. The number of wells and their spacing are based solely on the subsurface pressure distribution measured during a pilot-scale test.

The basic approach is outlined in figure 3.39 (on page 3.100). First, steady-state subsurface pressure distribution data are plotted as a function of distance from the pilot extraction well, usually on log-log or semi-log coordinates, and a best-fit line is then drawn. The "radius of influence" of the well is then graphically determined; it is that distance from the well where the pressure distribution has been extrapolated to reach some specified value. In practice, these specified values typically are 0.1 in. H_2O, 1.0 in. H_2O, or 10% of the applied vacuum at the extraction wellhead.

Figure 3.39
Flowchart for Radius-of-Influence Design Approach

1. Conduct pilot test and measure:

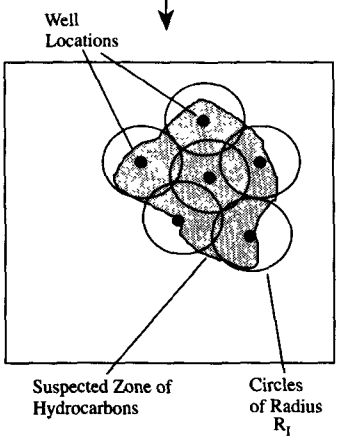
   • steady-state pressure distribution
   • flowrate -vs- pressure



2. Plot steady-state pressure distribution:

   • draw best-fit line through data
   • graphically determine R_I

3. Select well locations so that radii of influence overlap zone to be remediated



Once the radius of influence (R_I) has been determined, circles with this radius are drawn on a site map locating wells such that areas circumscribed by the circles overlap the zone to be remediated. After well locations have been specified, the designer selects extraction/injection pumps/blowers and a vapor treatment unit, often by one of the two approaches described in Subsections 3.4.7.1 and 3.4.7.2.

For air sparging, this approach has been extended to include the analysis of pilot-test unsaturated zone pressure distribution data, water table elevation data, and groundwater dissolved oxygen concentrations in an effort to establish an equivalent air-sparging radius of influence.

In the design of air-sparging vapor extraction systems, air-sparging well locations are selected first so that their radii of influence encompass the zone to be treated. Extraction well locations are then selected to assure that the extraction radii of influence extend between and around the air-sparging injection well radii of influence.

This approach is widely practiced because it is simple and graphical and closely imitates common groundwater recovery design practices. Unfortunately, this approach, at best, merely assures containment of contaminant vapors (the purpose of groundwater recovery system design) and does not provide for estimation of performance or long-term costs (Johnson and Ettinger 1994, illustrate that this design approach can result in extremely inefficient system designs in some cases).

3.4.7.4 Screening-Level Model Approaches

The major limitation of the simplistic design approaches discussed above lies in their failure to consider probable system performance factors (cleanup levels, duration of remediation, etc.) or constraints (costs, regulatory requirements, etc.). In order to incorporate these factors, the practitioner must apply predictive models that facilitate estimation of system performance as a function of a wide range of parameters, such as geologic conditions, contaminant type, and number of wells. Section 3.2 focused on the development of mathematical descriptions of relevant phenomena and showed that there were numerous modeling approaches ranging in complexity from analytical solutions to numerical algorithms requiring computer-based solutions. This section addresses the use of more accessible screening level models in the system design process. As an example, the approach presented by Johnson et al. (1990, 1991), which forms the basis for the HyperVentilate (Johnson and Stabenau 1991) software guidance system (distributed by the US EPA) is adopted. The data requirements include the following:

- extraction flow rate as a function of applied vacuum for conceptual well design;

- estimate of average residual soil concentration and volume of impacted soil;
- remedial goals - cleanup levels and remediation time;
- minimum volume of vapor to achieve required cleanup;
- steady-state pressure distribution from the well;
- effluent vapor concentration data from pilot test;
- geological cross-section map with contaminant distribution; and
- constraints – costs, regulatory requirements, etc.

The results of Subsection 3.2.9 can be applied in relating (1) the number of wells (N_{wells}) required to achieve the goals as a function of the flow rate to a single well ($Q(\Delta P)$ (cm^3/s)), (2) target remediation time ($\tau_{cleanup}$(s)), (3) average soil contaminant concentration ($<C_{soil}>$ (mg/cm^3-soil)), (4) volume of contaminant-containing soil (V_{soil} (cm^3-soil)), and (5) the parameter α (l-vapor/g-initial contaminant), which represents the minimum volume of vapor required to achieve cleanup per unit mass of contaminant as follows:

$$N_{wells} = \frac{V_{soil} < C_{soil} > \alpha P_{soil}}{Q(\Delta P)\tau_{cleanup}} \qquad [3.49]$$

The value of α can be determined by considering equilibrium modeling results (Subsection 3.2.9), possible mass-transfer resistances (Subsection 3.2.11), and laboratory soil column tests (Subsection 3.3.3). In the HyperVentilate approach, α is determined by first predicting (or measuring) the ideal equilibrium-based model result (Subsection 3.2.9) and then multiplying it by an efficiency factor determined from screening-level mass-transfer models (Subsection 3.2.11) or by estimating subsurface vapor dilution obtained from comparisons of soil gas and extracted vapor concentrations in the pilot test. Although the above discussion is oriented toward contaminant removal through volatilization, if biodegradation rates are known, they can also be incorporated in the modeling predictions of α.

The number of wells, N_{wells}, predicted by equation [3.49] should be regarded as a minimum estimate of wells required, as any real system performs less efficiently than an ideal system. Equation [3.49] provides a screening-level tool relating the number of wells, cleanup objectives, and operating conditions (flow rate). After either extraction pump characteris-

tics (required total flow and ΔP at each well) or the number of wells is specified, the remaining parameter is calculated from equation [3.49]. Once the number of wells and applied pressure are specified, steady-state pressure distribution data and the approach described in Subsection 3.4.7.3 are used in an attempt to assure that the system will contain the vapor. If it does not, additional wells will be needed. Figure 3.40 is a sample worksheet for this design approach.

Although this approach is discussed mainly in relation to vapor extraction systems, it is not difficult to extend it to the sparging of residual con-

Figure 3.40
Sample Worksheet for a Screening-Level Model Design Approach

Description of Data or Calculation	Value/ Result	Units
Site Data		
• attach geological cross section showing contaminant sampling results, subsurface conduits, and groundwater elevation		
• attach contaminant analyses results		
• average contaminant concentration in treatment zone $\langle C_S \rangle$		[g/g-soil]
• estimated volume of soil in treatment zone V_{soil}		[cm^3]
• approximate soil density ρ_{soil}	1.7	[g-soil/cm^3-soil]
• design flow rate per well Q@ΔP (attach pilot test data)		[L/min] @ [in. H_2O]
• radius-of-influence (attach steady-state pressure dist. figure)		[m]
Remedial Goals		
• cleanup target		[g/g-soil]
• desired duration of remediation $\tau_{cleanup}$		[d]
• cost goal		[$]
Calculations		
• minimum volume of vapor required (ideal case) α		[L/g-hydrocarbon]
• efficiency factor (describe basis for choice) ε		$0<\varepsilon<1$
• $N_{wells} = (V_{soil}\langle C_{soil}\rangle\rho_{soil}\,\alpha)/(Q\,\tau_{cleanup}\,\varepsilon * 1440$ min/d)		minimum # of wells
• total flow rate estimate = QN_{wells}		[L/min]
• additional wells required to achieve vapor containment		
• attach system layout schematic		

taminants in the saturated zone. Equation [3.49] would be interpreted as relating the minimum number of air injection wells required to the flow rate per air injection well and desired remediation duration.

At this point, an estimated total project cost can be calculated by specifying the costs for blowers, wells, piping, vapor treatment, and operation and maintenance, and another equation can be generated predicting total project cost as a function of duration of remediation. These operations are illustrated through an example in Chapter 4.0.

3.4.7.5 Detailed Numerical Modeling and Optimization-Based Approaches

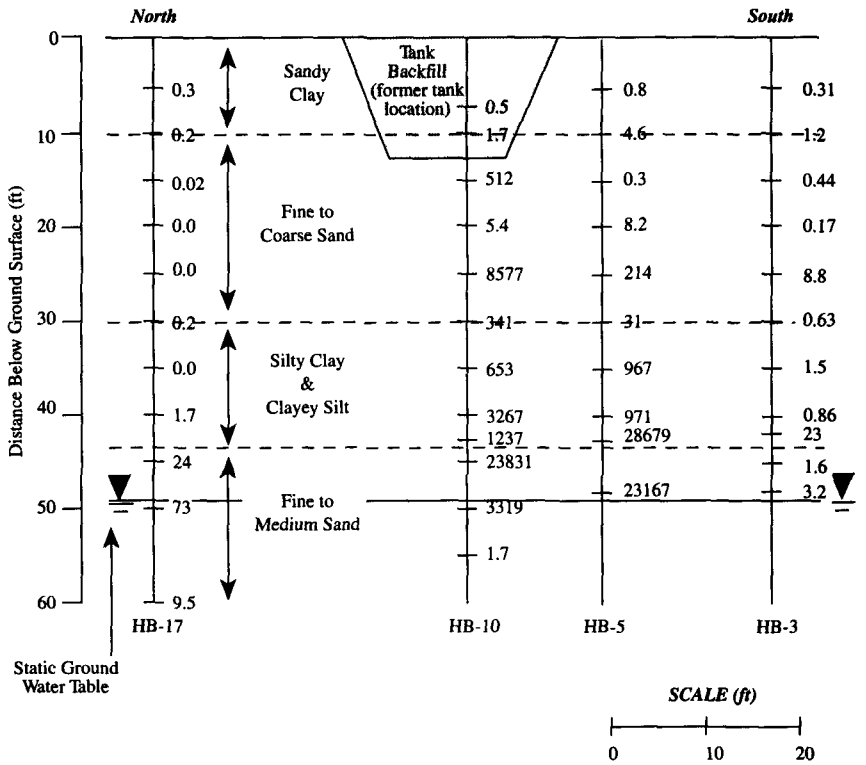
The approach presented in Subsection 3.4.7.4 can be extended through use of more complex mathematical models. Such models will usually require more data than are readily available; however, there are sites for which the projected cost of remediation warrants the expense of acquiring the needed data. To be used most effectively, complex modeling must be performed iteratively. The predictive model must be continuously refined, calibrated, and updated based on performance data collected from system operation. To date, accepted and validated models are not accessible to the general practitioner, although they may soon be (e.g., Joss and Baehr 1994).

3.4.8 Comparison of Various Design Approaches

To compare the several design approaches, figures 3.41 (on page 3.105) and 3.42 (on page 3.106) set forth summaries of results of many of the site characterization activities described in Section 3.3 for an example site. Although the example site has a number of distinct strata, for the sake of simplicity, this comparison focuses on the fine to medium sandy layer located between the clay layer and water table at a depth interval of about 13 to 15 m (43 to 49 ft) BGS. The determinations resulting from the several designs are tabulated in table 3.6 (on page 3.107).

For the design approaches outlined in Subsections 3.4.7.1 and 3.4.7.2, only the geological cross-section and contaminant distribution data presented in figure 3.41 are needed. Experience has shown that it is likely that a practitioner following one of these methods (and in the absence of pilot-test data) would install a system consisting of a single vapor extraction well screened roughly between 11 and 16 m (35 to 55 ft) BGS. This well might actually be an existing groundwater monitoring well. It would be connected

Figure 3.41
Total Hydrocarbon Distribution and Subsurface Geology for Sample Design Problem



Soil concentrations given in mg/kg-soil.

Reprinted by permisssion of CRC Press from "Soil Venting at a California Site: Field Data Reconciled with Theory. Hydrocarbon Contaminated Soils and Groundwater: Analysis, Fate, Environmental and Public Health Effects" by P.C. Johnson, C.C. Stanley, D.L. Byers, D.A. Benson, and M.A. Acton, Remediation, Vol. I, editors, P.T. Kostecki and E.J. Calabrese, Lewis Publishers. Copyright 1991 by CRC Press.

to a 47 L/sec (100 standard ft^3/min) capacity blower and a vapor treatment unit. It is also very likely that in these geologic conditions, the user will not have anticipated the need for a groundwater drawdown system and that he or she will soon find the extraction flow decreasing to zero as the water level rises above the screened interval. Water would not be pulled all the

way up the well to ground surface, as the maximum upwelling that can be created by a perfect vacuum is 10.33 m (33.9 ft).

In the radius-of-influence design approach, described in Subsection 3.4.7.3, the information in figure 3.41 is used along with the pilot-test data in figure 3.42. Based on the steady-state pressure data in figure 3.42, common practice would yield a radius of influence of approximately 18 m (60 ft). In comparison, figure 3.41 indicates that most hydrocarbons are distributed within a radial distance of 9 m (30 ft), and it appears that a single well

Figure 3.42
Summary of Design Data for Sample Design Problem

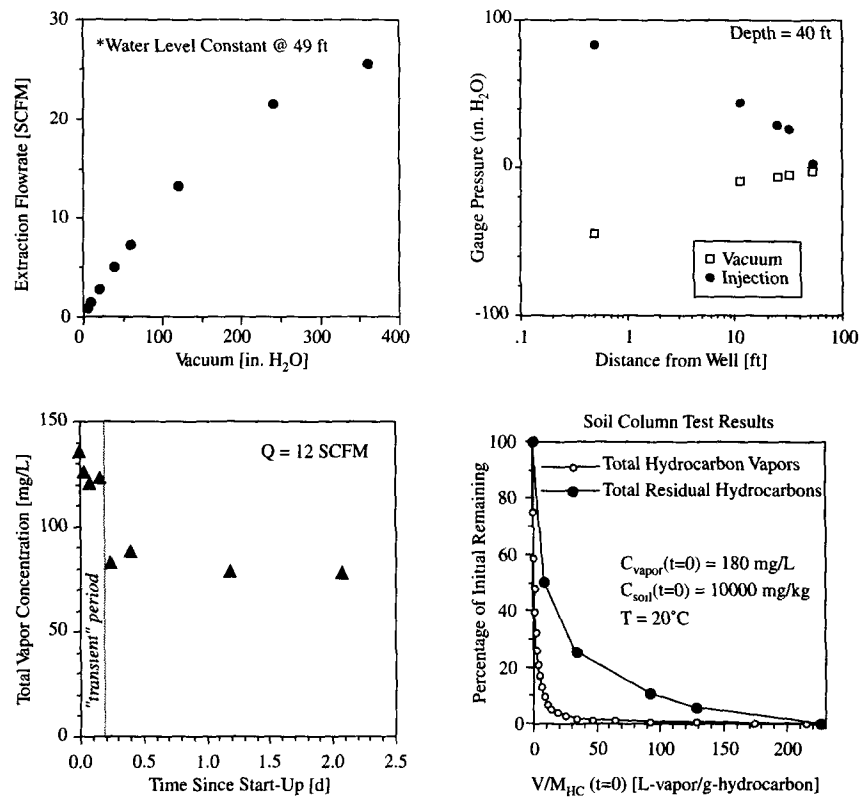


Table 3.6
Results of Example Design Problem

Parameter	Design Approach A, B	C	D	E
Design Specifics				
• number of wells	1	1	45	NA
• total flow rate [SCFM] @ required vacuum [in. H_2O]	available blower	available blower	450 @ 28 in	NA
• vapor treatment unit capacity [SCFM]	100	100	450	NA
System Expectations				
• hydrocarbon level reduction [%]	?	?	>95%	NA
• duration of cleanup [d]	?	?	360	NA

A,B - Intuition/Experience-Based Empirical Approach and Minimization of Capital Expenses (Subsection 3 4 7 1 and 3 4 7 2)
C - Radius of Influence-Based Approach (Subsection 3 4 7 3)
D - Screening Level Model-Based Approach (Subsection 3 4 7 4)
E - Detailed Numerical Modeling and Optimization-Based Approaches (Subsection 3 4 7 5)
NA - this level of design not yet justifiable for this site
? - unknown for this design procedure

should be sufficient for remediation. Therefore, the vapor extraction system designed by this process is identical to that resulting from the methods of Subsections 3.4.7.1 and 3.4.7.2. It is likely, however, that in this case the practitioner would recognize the necessity of incorporating a groundwater drawdown system, as significant upwelling would have been discovered in the pilot test.

Under the approach described in Subsection 3.4.7.4, full use is made of the complete pilot-test data. In order that equation [3.49] may be used, the following parameter values are assigned:

$$V_{soil} = \pi\,(30\text{ ft})^2 \times 6\text{ ft} = 17{,}000\text{ ft}^3 = 4.8 \times 10^6\text{ m}^3$$

$$\langle C_{soil}\rangle = 20{,}000\text{ mg/kg-soil} = 0.020\text{ g/g-soil} \times 1.7\text{ g/cm}^3\text{-soil} = 0.034\text{ g/cm}^3\text{-soil}$$

$$\alpha = (200\text{ L/g-hydrocarbon } (3{,}200\text{ ft}^3\text{/lb-hydrocarbon}) \text{ (ideal case)})/(0.50 \text{ (efficiency)}) = 400\text{ L/g-hydrocarbon } (6{,}400\text{ ft}^3\text{/lb-hydrocarbon})$$

$$Q(\Delta P) = 10 \text{ standard ft}^3\text{/min @100 in. } H_2O = 4.7 \text{ L/sec}$$

$$\tau_{cleanup} = 360 \text{ d} = 3.1 \times 10^7 \text{ sec}$$

The volume of soil, V_{soil}, is obtained by approximating the hydrocarbon-containing zone as a cylinder of radius 9 m (30 ft) and depth 1.8 m (6 ft), as estimated from the data in figure 3.41 (on page 3.105). The average soil concentration $<C_{soil}>$ in this zone is assumed to be 20,000 mg-hydrocarbon/kg-soil, consistent with data given in figure 3.41. In order to assign a value to the minimum volume of vapor required to achieve the desired degree of remediation α, the soil column test data and pilot-test vapor concentration data in figure 3.42 (on page 3.106) are used. Soil column test data indicate that about 200 L-vapor/g-initial residual (3,200 ft^3/lb-initial residual) hydrocarbon is required to achieve a reduction of 95% in the total hydrocarbon concentration under ideal conditions (it is more likely that modeling results would be sufficient in this case, but soil column data are used for purposes of illustration), while effluent vapor concentration monitoring results from the pilot test suggest that only half the extracted flow is actually passing through hydrocarbon-containing soils. Thus, α is modified to account for this efficiency (about 50%) and a value α = 400 L-vapor/g-initial residual (6,400 ft^3/lb-initial residual) hydrocarbon is assigned. Flow-rate data combined with knowledge of groundwater drawdown system limitations indicate that the maximum extraction flow rate is likely to be about 4.7 L/sec (10 standard ft^3/min) per well in this situation, where airflow is confined between the clay layer and groundwater. In this example, the goal of a remediation duration of one year (360 d = 3.1×10^7 sec) is assumed. As indicated in table 3.6 (on page 3.107), the prediction resulting from equation [3.49] is that a minimum of 45 wells will be required to remediate this site. Consequently, the system must be sized to handle and treat 45 x 4.7 L/sec (10 standard ft^3/min) = 212 L/sec (450 standard ft^3/min) of vapor at 100 in. H_2O gauge vacuum.

For this example, more sophisticated predictive models were not used, mainly because it is not likely that they will be used in the near future for sites of this scale. The reader should see, however, that there might be a certain benefit in using more sophisticated models for this site, as the large number of wells predicted results mainly from flow restrictions imposed by groundwater upwelling. With more complex predictive tools, the user could explore complex system designs using air injection wells and state-of-

the-art groundwater extraction systems to partially overcome this constraint. It should be noted that even though 45 wells would not be a typical design, it is unlikely that other technologies currently available would be effective in remediating this site in the desired time frame.

In comparing the system designs resulting from the several approaches, as table 3.6 (on page 3.107) indicates, one sees little difference among the systems designed under the methods of Subsections 3.4.7.1, 3.4.7.2, and 3.4.7.3. In each case, a simple, single extraction well system is prescribed. But the predictions resulting from the more sophisticated (and reliable) screening level model approach yield a prohibitively high density of extraction wells, a result that should lead the user to question the efficacy of vapor extraction at this site. Based on the screening-level model predictions, systems installed by the first three methods are unlikely to achieve satisfactory remediation in a reasonable time frame, although there is nothing in the design procedure to indicate this result. Thus, this exercise illustrates the inherent drawbacks of simplistic design practices that are commonly used.

3.4.9 Other Design Considerations

There is an increasing trend toward using integrated and phased approaches wherein multiple technologies are used together or in sequence to achieve the desired remediation goal. In many cases, additional advantages result from combining technologies. In the preceding example, a groundwater recovery system could be used to contain the soluble groundwater plume as well as to enhance the vapor extraction system performance by minimizing groundwater upwelling. The practitioner is urged to be alert to possible synergistic effects as system design progresses.

3.5 *Costs*

It is common to see remediation costs of ex situ technologies (incineration, thermal desorption, soil washing, etc.) quoted on a per volume of soil treated basis, and it would be useful if costs of vapor extraction-based technologies were similarly quoted. Unfortunately, given the dependence on site geology, type of contaminant, and other factors, especially depth to contamination, costs of vapor extraction-based technologies cannot be

meaningfully expressed on a per-volume basis. Estimates can be made for major capital equipment costs, and these have been included in the text. The major portion of total remedial costs in most cases is that for operating labor, maintenance, and monitoring. These costs can best be minimized by specifying systems under a design method that incorporates remedial goals and by employing equipment requiring little maintenance.

3.6 Performance Monitoring

As observed in Section 3.4, the design of vapor extraction-based systems is, for all practical purposes, a continuous process that begins with the initial pre-construction design and continues after the system is installed and operating. Monitoring data are relied upon in assessing system performance, calibrating models, and guiding necessary operational changes and equipment modifications. System monitoring and data presentation requirements have been presented to some extent in the discussion of field-pilot tests (Subsection 3.3.4) and system design (Section 3.4), and the reader is referred to those discussions. Here, data and data presentation options for full-scale continuously operating systems are discussed in more detail. Once again, there is a wide range of monitoring options and it is up to the practitioner to select monitoring requirements based on the particular need for information. Requirements are presented here in relative order of importance in assessing system performance. While there is flexibility in choosing monitoring strategies, as table 3.7 (on page 3.111) indicates, there is a minimum level of information that must be gathered in order to make basic performance evaluation decisions.

3.6.1 Primary Process Variables (Vapor Flow Rates, Pressure, Extracted Gas Characterization)

The most straightforward means of assessing vapor extraction-based process performance is to monitor the flow and composition of the extracted gases. This is the minimum monitoring required and is done to track mass-removal rates, compositional changes, and mass- and vapor-flow rates. Interpretation of the data can lead to identification of permeability changes and mass-transfer limitations.

Table 3.7
Process Monitoring Options and Data Interpretation

Data Interpretation/Analysis Requirement	Data Collection Requirement
• concentration vs. time • composition vs. time • flowrate 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 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
• define 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

b - applicable for bioventing applications, * - optional, or as required, s - relevant to air sparging

Data Collection Requirement 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, soil moisture content*
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

Flow rate Q (volume/time) may be measured by a number of means and should be corrected to some volume per unit of time Q^* at a standard pressure and temperature and is expressed:

$$Q^* = Q\ (P/1\ \text{atm})(293\ ^\circ\text{K}/T) \qquad [3.50]$$

where P (atm) and T (°K) are the absolute pressure and absolute temperature measured at the flow-rate measuring device, respectively. Examples of

acceptable expressions of flow rate units are standard m^3/hr or standard ft^3/min (this implies flow rates corrected to 1 atmosphere and 20°C (68°F)). The use of standard units is especially important, as most gas analyses are expressed on similar bases and these two values are multiplied to assess mass-removal rates.

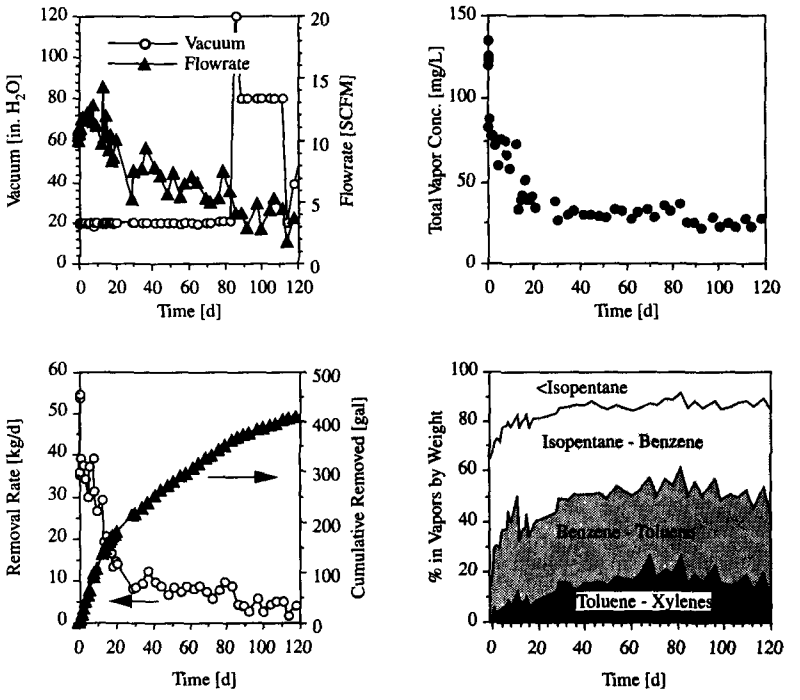
A variety of methods are available for measuring gas-flow rates. Pitot tubes or orifice plates combined with an inclined manometer or a differential pressure gauge are acceptable for measuring flow velocities of at least 400 m/min (1,300 ft/min). For lower flow rates, a rotometer will typically provide a more accurate measurement. As mentioned previously (Subsection 3.3.4 and Section 3.4), flow meters should be installed to measure flow rates from all extraction/injection wells, as well as combined total extraction/injection flow. In order to be able to express the measured flow rate on a standard (1 atm, 20°C) basis, the pressure at the point of flow measurement must be known. All extraction well flow meters and pressure gauges must be placed between the wellhead and first downstream junction or valve (or upstream, in the case of air-injection wells). There are also other guidelines for flow-meter placement that are specific to different types of flow meters (e.g., placement at least 10 pipe diameters away from constrictions).

Extraction gas pressure should be monitored at the extraction wellhead. Typically, this is done by a permanently installed pressure gauge or a "quick release" connection that facilitates measurement. The pressure measurements required for flow-rate measurement are also useful in interpreting system operation and performance. Pressure changes over time (at constant flow rate) indicate soil-gas permeability changes and usually are the result of soil-moisture changes (due to upwelling, infiltration, or drying). Figure 3.43 (on page 3.113) presents pressure and flow rate data for a vapor extraction system on the same graph. It can be seen that a permeability reduction is occurring with time, as the flow rate is decreasing with time while the applied vacuum is held constant. In this case, the reduction was attributed to groundwater elevation changes (Johnson et al. 1991). Similar injection pressure vs. flow-rate plots should be made for air sparging, bioventing, and other vapor extraction-based technologies employing air injection wells.

Exhaust gas is monitored in order to determine contaminant removal rates and assess mass-transfer limitations. Gas composition measurements typically include, at a minimum, some measure of the contaminant concen-

tration and composition and may include respiratory gas measurements (Subsection 3.5.2). A variety of techniques are available for measuring contaminant concentration in the extracted gas; the choice in a given situation may be dictated by regulations or permitting procedures. Typically, a flame ionization detector (FID), a photoionization detector (PID), or an electrochemical detector (e.g., a "hot wire") is used. If the contaminant is a chlorinated organic, an electron capture detector (ECD) or Hall-type detec-

Figure 3.43
Presentation of "Minimum" Data Collection Needs for Vapor Extraction Systems



Adapted from Johnson, P.C., Stanley, C.C., Byers, D.L., Benson, D.A., Acton, M.A., Soil Venting at a California Site: *Field Data Reconciled with Theory*, 274-275, in *Hydrocarbon Contaminated Soils and Groundwater*, Vol. 1, Kostecki, P.T., Calabrese, E.J., Eds., Lewis Publishers (subsidiary of CRC Press), Boca Raton, Florida, 1991. With Permission.

tor may be more appropriate. The detector may be coupled with a gas chromatograph to separate peaks.

For most nonhalogenated organics, the FID is currently the recommended detector. Individual peaks of a chromatographic column are quantified and used to assess composition. In the absence of chromatographic separation, the total detector response is used as an indication of total contaminant concentration. For some organics, such as benzene, PID detectors are often used because of their high sensitivity; however, this sensitivity is compound-specific and highly variable. Thus, the PID is a poor indicator of total contaminant concentration and should not be used for this purpose unless it is known that the PID is equally responsive to all compounds in the hydrocarbon vapor stream. A PID usually works best when a single compound is present and its response is known. A hot wire detector is used to monitor explosive environments and is adequate for monitoring total contaminant response at higher concentrations (above 100 ppm_v).

Currently, concentrations are most often reported by laboratories as ppm_v, parts per million by volume (sometimes called L/L). This is a measure of the partial pressure of the gas and should not be confused with parts per million by mass or mass per volume (i.e., mg/kg or mg/l). Concentrations may be expressed also as mass per unit volume of vapor, such as $\mu g/m^3$ or mg/l. The basic relationship between partial pressure and mass per unit volume is:

$$C_{vapor}(\mu g / m^3) = C_{vapor}(ppm_v)\frac{10^{-6} MW}{RT} \qquad [3.51]$$

where MW (μg/mole) denotes the molecular weight of the contaminant *used to calibrate the detector* (may not be the actual contaminant being monitored) and R represents the gas constant (8.2×10^{-5} m^3-atm/mole-K), and T = 293 °K (20°C). Equation [3.51] is essentially the Ideal Gas Law where C_{vapor} (ppm_v) 10^{-6} represents the partial pressure of the gas being monitored. It is important to recognize that expression of gas concentrations in volume/volume units is meaningless unless one also specifies the calibration compound. Thus, a total contaminant concentration of 100 ppm_v measured on a portable FID calibrated to methane must be expressed as 100 ppm_v-methane to have meaning (e.g., a gasoline vapor stream reported to have a total contaminant concentration of 100 ppm_v-methane is not equivalent to a reported total concentration of 100 ppm_v-hexane).

For vapor extraction-based technologies, vapor concentrations should be reported and recorded in mass/volume units, as this facilitates the calculation of removal rates R_v (mass/time) and any confusion is eliminated, where R_v is the product of the flow rate (volume/time) and vapor concentration C_{vapor} (mass/volume):

$$R_v = Q^* C_{vapor} \qquad [3.52]$$

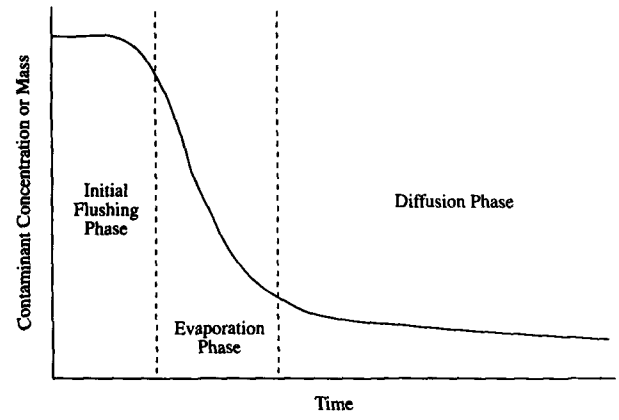
Here, use of the flow rate expressed in standard units, Q^*, is indicated as most gas samples are analyzed from sample containers maintained at 1 atm pressure. The cumulative contaminant recovered by volatilization, T_v (mass), is then computed by integrating the recovery curve over time:

$$T_v = \int_{t=0}^{t} R_v dt \qquad [3.53]$$

Figure 3.43 (on page 3.113) presents sample total hydrocarbon vapor concentrations, calculated removal rates, and cumulative amount recovered by volatilization for a vapor-extraction application.

As a general rule for vapor extraction-based technologies, the contaminant concentration in extracted gas usually declines over time, unless significant process modifications are made after start-up (such as the installation of an air-sparging system). In many soil vacuum extraction systems, three performance phases are evident. These are illustrated conceptually in figure 3.44 (on page 3.116). During the initial "flushing phase", the first volume of soil gas is extracted from the contaminated soil. Contaminant vapor concentrations are relatively high during this phase, reflecting the long-term soil-gas equilibria condition. During the second "evaporation phase", contaminants are rapidly removed from the more permeable soils, through which extracted gas readily flows. As these more permeable channels become cleaner, the final, or "diffusion phase," begins. During the diffusion phase, contaminants are removed more slowly from the less-permeable portions of the formation and the removal rate is limited by diffusion from the less-permeable soils into the more-permeable flow channels (Subsection 3.2.11). In some cases, all three phases are not evident and the shape of the curve depends greatly on the contaminant mixture and site conditions.

Figure 3.44
Generalized Concentration or Mass of Contaminant Observed In Gas Extracted from a Vacuum Extraction System

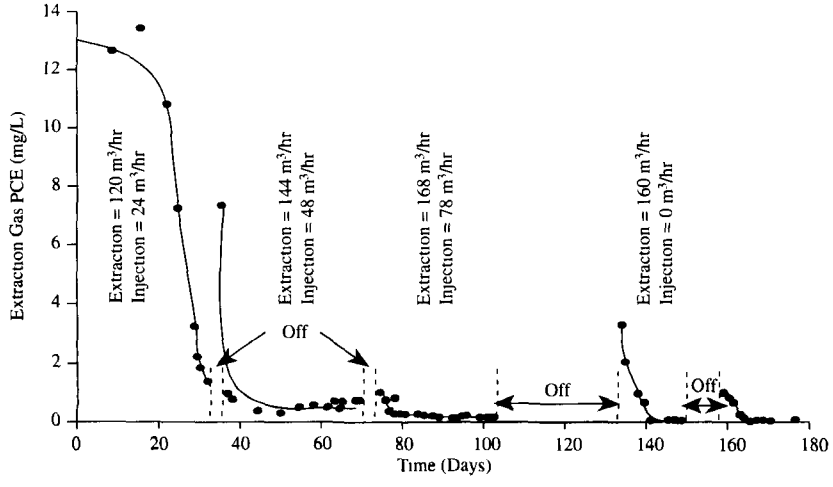


If a vapor extraction system is shut down during the diffusion phase, contaminant vapors continue to diffuse away from the contaminant source and the average soil-gas concentration in the zone of induced airflow slowly increases. Consequently, higher concentrations are observed when the system is restarted. This phenomenon is referred to as the "restart spike." Figure 3.45 (on page 3.117) illustrates this phenomenon at a tetrachloroethylene (PCE)-contaminated site. In this study, both extraction and air injection were used.

While total hydrocarbon analysis of extracted vapors is used to determine the removal rate and cumulative amount removed, this data cannot be used to determine whether declines in vapor concentration are the result of reductions in residual contaminant levels, composition changes (i.e., "lighter" compounds being removed first), or mass-transfer limitations (Subsection 3.2.11). In addition, these data are usually insufficient to satisfy regulations, which may require specification of selected compounds (e.g., benzene). For this reason, it is recommended that a compositional analysis be performed on selected extraction gas samples. Composition analyses are discussed in Subsection 3.3.1.

In a highly diffusion-limited situation, the relative concentrations of high-vapor pressure and lower-vapor pressure compounds will not change greatly over time, even if the total contaminant concentration drops substantially. Conversely, if a site is not highly diffusion-limited, the relative ratio of highly volatile to less volatile contaminants will decrease more rapidly. As an example, figure 3.43 (on page 3.113) presents composition data from the first 120 days of vapor extraction at a service station site (Johnson et al. 1991). The general trend exhibited by the vapor concentration data is consistent with expectations; vapor concentrations are declining substantially during this time frame. In addition, the vapors of the relatively "heavier" hydrocarbon components are gradually becoming richer. The compositional change over the 120 day period, however, cannot account for the 100-fold decrease in vapor concentration and this indicates remediation is being controlled by mass-transfer limitations.

Figure 3.45
Tetrachloroethylene (PCE) Concentration in Extracted Gas from a Site Near Milan, Italy



Data from Castalia 1990

3.6.2 Respiratory Gas Monitoring

For bioventing applications, or where an aerobic biodegradation contribution to removal is to be estimated, the data discussed in Subsection 3.5.1 should be supplemented by respiratory gas (O_2 and CO_2) monitoring data. Monitoring the extracted vapor stream is discussed in this subsection and using in situ soil-gas respiratory gas monitoring is discussed in Subsection 3.5.5.3. Here, it is assumed that complete aerobic degradation of the contaminant occurs; for example, the degradation of benzene is expressed as:

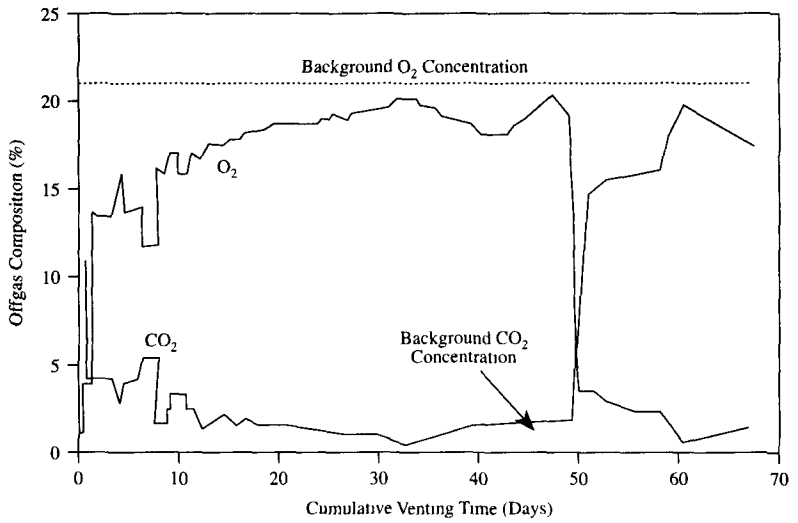
$$C_6H_6 + \frac{15}{2}O_2 \rightarrow 6CO_2 + 3H_2O \qquad [3.54]$$

Equation [3.54] indicates that by monitoring oxygen utilization or CO_2 production one should be able to estimate aerobic biodegradation rates. An important consideration commonly overlooked in practice, however, is that there may be other in situ processes (natural respiration, abiotic reactions, etc.) that use or produce CO_2 and O_2. Currently, it is felt that monitoring O_2 use provides a better estimate of biodegradation than does measuring CO_2 production, because of the presence of carbonates, especially in sandy soils. Working on a diesel-contaminated site in the Netherlands, van Eyk and Vreeken (1989) found that much of the CO_2 produced by biodegradation went into carbonate formation and was not evolved as gaseous CO_2. Hinchee and Ong (1992), working at a number of bioventing sites, found that, in low-pH soils (pH <6.0), biodegradation estimates based on CO_2 were comparable to estimates based on O_2. At higher pH levels, however, CO_2-based estimates were found to substantially underestimate biodegradation.

Typically, at the onset of remediation, O_2 concentrations are low (<5% v/v), and CO_2 (>15% v/v) concentrations are high. Over time, increases in O_2 and decreases in CO_2 are observed in the extracted vapor streams as well as in soil-gas monitoring probes. When the O_2 and CO_2 concentrations approach background levels, biodegradation has slowed and either the site is clean of biodegradable compounds, or some other limitation to biodegradation has intervened.

Figure 3.46 (on page 3.119) presents data collected at a JP-4 contaminated site. The O_2 and CO_2 concentrations in the extraction gas over a 68-day period are illustrated. The venting system was shut off on day 48,

Figure 3.46
Oxygen and Carbon Dioxide Concentrations in the Venting of Gas Versus Time at the Hill AFB, Utah, Soil Venting Site December 18, 1988 to April 1, 1989



Source Smith, Dupont, and Hinchee 1991

corresponding to the recorded drop in O_2 concentration. The "background" CO_2 and O_2 levels are extraction gas measurements from a similar vapor extraction process conducted at a nearby uncontaminated site.

In using either O_2 or CO_2 measurements to estimate biodegradation, it is necessary to estimate background O_2 consumption and/or CO_2 production. For reference, the atmosphere contains approximately 20.9% O_2 and 0.35% CO_2. Natural, uncontaminated soil gas, however, contains somewhat less O_2 and more CO_2 than the atmosphere because of natural soil respiration (figure 3.46). This was shown by both Dupont, Doucette, and Hinchee (1991) and Miller, Hinchee, and Vogel (1991). Vent wells and soil vapor extraction systems were installed in nearby uncontaminated soils. These soil vapor extraction systems were operated at rates similar to the soil vapor extraction systems in contaminated soils in order to quantify the back-

ground respiration rate. This approach, although ideal, is not feasible at many sites.

Given O_2 and/or CO_2 levels (% by volume) in the extracted vapors for the remediation and background sites, loss rates due to aerobic biodegradation, R_b (mass/time), are estimated through the following process:

1. Calculate molar uptake of oxygen, M_b (moles O_2/time), correcting oxygen depletion for natural respiration from a "background" site:

$$M_b\left(\frac{moles-O_2}{d}\right)=Q\left(\frac{m^3}{d}\right)\left(\frac{(C_b-C_r)}{100\%}\right)\frac{P}{RT}\left(\frac{moles-O_2}{m^3-vapor}\right) \qquad [3.55]$$

   where C_b (% O_2), C_r(% O_2), P (atm) , R (8.2 x 10^{-5} atm-m^3/mole-K), and T (°K) denote the concentration of O_2 measured in extracted vapors at the background site (under similar operating conditions), concentration of O_2 measured in extracted vapors at the remediation site, pressure at the flow rate monitoring point, gas constant, and absolute temperature at the monitoring point, respectively; and

2. Divide M_b ((moles-O_2/d) by the stoichiometric ratio S (moles O_2/ moles contaminant), and multiply by the contaminant (C) molecular weight, M_w (g/mole), to obtain the contaminant degradation rate R_b (g/d):

$$R_b\left(\frac{g-C}{d}\right)=M_b\left(\frac{moles-O_2}{d}\right)\left(\frac{1}{S}\right)\left(\frac{moles-C}{moles-O_2}\right)M_w\left(\frac{g-C}{moles-C}\right) \qquad [3.56]$$

   For example, assuming the degradation of hexane (C_6H_{14}):

$$C_6H_{14}+\frac{19}{2}O_2\rightarrow 6CO_2+7H_2O \qquad [3.57]$$

   then S = 19/2 moles of O_2 are consumed for each mole of hydrocarbon degraded.

An alternative approach based on carbon isotope analysis of extraction gas samples can be used to distinguish, at least qualitatively, between background CO_2 and CO_2 resulting from hydrocarbon degradation. Here, advan-

tage is taken of the knowledge that petroleum hydrocarbons tend to have a higher ratio of $^{12}C/^{13}C$ relative to other carbon sources in the subsurface. Therefore, by measuring the $^{12}CO_2/^{13}CO_2$ ratio in extracted gas from contaminated and uncontaminated sites, an inference as to the source of the CO_2 can be made. Aggarwal, Means, and Hinchee (1991) describe a method for determining the source of CO_2-hydrocarbon biodegradation vs. background respiration based on the stable carbon isotope composition of the soil gas. This can be a relatively inexpensive (≈$25 to $150/sample) qualitative approach to determining whether aerobic biodegradation of hydrocarbons is occurring.

3.6.3 Cost

Costs should be monitored during the remediation process in order to be able to evaluate the cost-effectiveness of operating the vapor extraction-based system. Following are cost components of vapor extraction-based systems:

- Capital Cost: The cost of system design, construction, and installation; it usually includes costs of permitting and pre-operational studies;
- Utilities: Includes electrical usage by blower/vacuum pump and auxiliary equipment operation, as well as the cost of any supplemental fuel for offgas treatment;
- Operation and Maintenance: The cost of basic system operation, maintenance, and repair; in most cases, labor is the most significant component of this cost;
- Monitoring: The most variable cost associated with a vapor extraction-based technology system's operations, and at many sites the largest component; it consists of analytical charges and labor, with labor frequently being the largest element; and
- Miscellaneous: All other costs, including equipment or space rental, ongoing permit costs, and the loss of property use associated with the vapor extraction-based system.

To evaluate cost-effectiveness of the vapor extraction-based technology system, costs and mass of contaminant removed/degraded should be plotted vs. time. For example, the unit cost for contaminant removal in dollars per pound recovered can be calculated and displayed as a function of time. The

resulting plot usually resembles an exponential increase, reflecting that as the remediation nears completion cost per unit mass of contaminant removed increases. In some cases, it may be possible to negotiate an end point based upon this economic analysis.

3.6.4 Environmental Factors

In addition to the process variables discussed above, certain environmental variables may influence vapor extraction-based technology performance. Even if they do not directly affect performance, they may influence interpretation of monitoring data. These include barometric pressure, temperature, relative humidity, and rainfall.

A variety of conventional techniques are available to measure barometric pressure. In addition, in most areas, weather reports that include accurate, reliable barometric pressure measurements can be obtained. It is more common, however, simply to assume standard barometric pressure, adjusted for altitude. Barometric pressure fluctuations can significantly affect in situ vapor-phase pressure measurements, as these are always relative to the current atmospheric pressure. This effect is most significant when attempting to measure induced pressure changes that are of the same magnitude as the barometric pressure fluctuations (as when measuring pressure distributions away from injection/extraction wells during short-term pilot tests). Such effects can be significant in regions with large diurnal temperature fluctuations (e.g., daytime temperature of 38°C (100°F) to nighttime temperature of 16°C (61°F)).

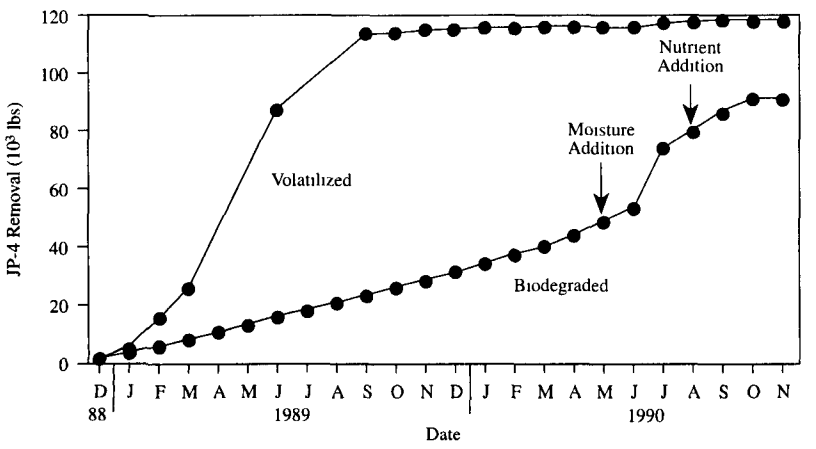
Air temperature fluctuations over a few hours or days have little or no impact on subsurface temperature. In situ soil temperatures and extracted gas temperature may be simply monitored with thermocouples and thermistors. Some authors have reported using extracted gas and in situ temperature measurements as qualitative indicators of microbiological activity. For the most part, however, temperature measurements currently do not play an important role in most monitoring plans, except in very harsh climates and where there are technology modifications discussed in Section 3.6.

Soil moisture content can have a significant impact on vapor extraction-based system performance. A high-soil moisture content can cause reductions in soil-gas permeability and diffusivity, which result in poor gas flow

and poor mass-transfer characteristics. A low-soil moisture content (below the wilting point) can slow microbial degradation. Dupont, Doucette, and Hinchee (1991) found soil moisture to be a very important variable in bioventing. Another consideration is that under very dry conditions, a soil's adsorptive capacity for hydrocarbons increases, thereby adversely affecting the hydrocarbon/soil equilibria.

Measurements of relative humidity in the extraction gas and ambient air (or injection air), coupled with rainfall measurements, can be used to develop a rough in situ water-mass balance. The difficulty lies in estimating infiltration from rainfall. This exercise, however, is useful in determining the rate of drying induced by a vapor extraction-based process. Soil moisture may also be measured directly. Smith, Dupont, and Hinchee (1991) utilized neutron probe access tubes to measure in situ soil moisture. Figure 3.47 illustrates the results of their measurements before and after the surface application of water at a site at Hill AFB, Utah. Soil moisture may also be

Figure 3.47
Cumulative Hydrocarbon Removal (Volatilized and Biodegraded) Hill AFB, Utah, Soil Venting Site (December 18, 1988 to November 14, 1990)



Source: Smith, Dupont, and Hinchee 1991

measured gravimetrically in collected soil samples. The authors are not aware of any optimal soil moisture levels; the practitioner should be aware that system performance can be enhanced or impaired by changes in soil moisture levels, and there are few practical options for controlling the soil moisture (capping to reduce infiltration, irrigating to increase moisture content, etc.). In general, in arid environments and high-permeability soils, low-soil moisture effects are more likely to be seen. In more moist environments and low-permeability soils, high-soil moisture effects are more likely to be seen.

3.6.5 Subsurface Monitoring

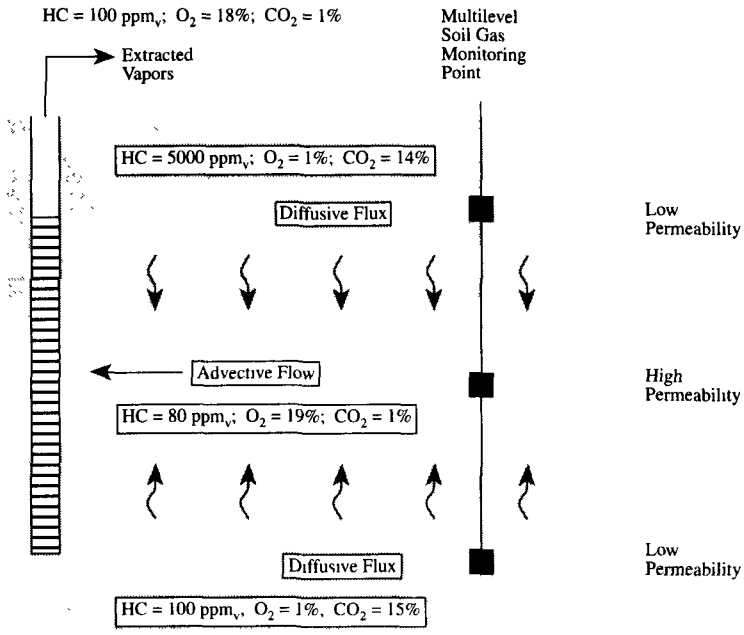
When the extracted hydrocarbon vapors and environmental factors only are monitored, ability to assess system performance is limited; in particular, these data generally cannot be used to determine the extent of remediation or the factors and phenomena that are limiting system performance. Extracted gas vapors represent a volume average of all vapors flowing to a given extraction well. Therefore, measurements are biased toward those zones that supply greater flow, as is illustrated in figure 3.48 (on page 3.125). At best, monitoring aboveground process streams allows estimation of the removal rates by volatilization, cumulative amount volatilized, and, in some cases, aerobic biodegradation rates.

To gain a better picture of the extent of remediation and processes that affect system performance, some level of in situ monitoring is required. A number of options for doing this are discussed in the Subsections immediately following.

3.6.5.1 In Situ Soil-Gas Monitoring

Soil-gas monitoring is a quick and effective means for assessing the effect of remediation in an area around a soil-gas monitoring location. Soil-gas samples can be obtained over time and analyzed for total hydrocarbon concentration and composition. Over time, a reduction in concentration and shift in composition will be seen in those areas that are being remediated. Table 3.8 (on page 3.126) presents soil-gas data from a vapor extraction site. These data illustrate how some areas at a vapor extraction site were more effectively remediated over time. For example, the area surrounding location HB-7D did not show as significant a reduction in total hydrocarbon concentrations as other areas.

Figure 3.48
Schematic of Hypothetical Subsurface Flow and Relation Between Extracted Gas Concentration and In Situ Soil Gas Concentrations in Stratified Flow System



Soil-gas samples can be extracted from small diameter tubes driven into the soil, or from tubes permanently installed in a borehole as shown in figure 3.49 (on page 3.127), which also shows the optional installation of thermocouples). Although the construction of in situ soil-gas monitoring points is relatively simple, a number of factors deserve careful attention. In general, numerous narrowly-screened points are more useful than one single, broadly-screened point. Small-diameter tubing (0.6 cm (1/4 in.) or even 0.2 cm (1/16 in.)) is usually preferred to larger diameter tubing, as this reduces the volume of gas in the sampling tube and allows easier, more effective purging and sampling. Often the tubing is strapped to the outside of a sup-

Table 3.8

Vadose Zone Monitoring Well Vapor Concentrations and Compositions Measured During a Vapor Extraction Application

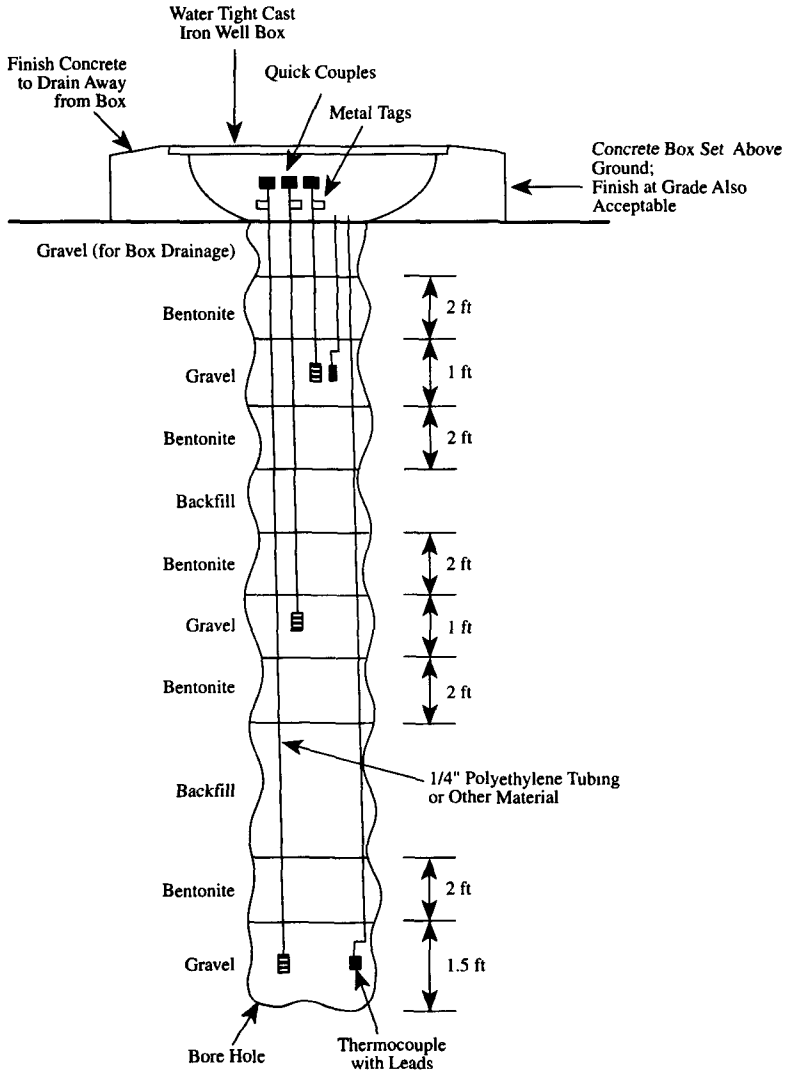
Well ID	Date	Distance from Venting Well HB-25 (ft)	Depth (ft)	Total Hydrocarbons (mg/l)	% Vapor Composition Boiling Point Fraction 1	2	3	4	5
HB-6S	1/24/89	8	10	13	15.4	34.6	30.8	19.2	0.0
HB-6S	12/9/89	8	10	0.15	13 3	18.7	25.3	26.0	16.7
HB-6D	1/24/89	8	40	308	32.0	49.1	17.6	1.2	0.0
HB-6D	1/25/89	8	40	168	37.8	50.0	11.8	0.4	0.0
HB-6D	2/28/89	8	40	91.8	27.7	52.9	18.0	1.4	0.0
HB-6D	12/9/89	8	40	37 2	13.1	39.1	38.1	9.2	0.6
HB-7S	1/24/89	15	10	32.7	45.6	33.3	15.9	5.2	0.0
HB-7S	1/25/89	15	10	28 9	51 9	34.6	10.7	2.8	0.0
HB-7S	2/28/89	15	10	11.5	27.0	25.2	32.2	15.7	0.0
HB-7S	12/9/89	15	10	3.2	14.2	38.5	10 7	51.3	20.0
HB-7M	1/24/89	15	25	298	36 2	50 8	12.3	0.7	0.0
HB-7M	1/25/89	15	25	47 4	34.8	26.8	27.0	11.4	0.0
HB-7M	2/28/89	15	25	20 2	17 3	32.7	38.6	11 4	0.0
HB-7M	12/9/89	15	25	16 6	0.5	5.6	46.7	44.7	2 4
HB-7D	1/24/89	15	40	239	43.2	48.3	8.2	0.3	0 0
HB-7D	2/28/89	15	40	241	28 6	42.4	25.5	3.5	0 0
HB-7D	12/9/89	15	40	106	26 9	41.5	27.9	3.4	0 2
HB-14S	1/24/89	30	10	6 3	58.7	27 0	12.7	1.6	0.0
HB-14S	12/9/89	30	10	0 2	27 1	33 3	12 4	14.3	12.9
HB-14M	1/24/89	30	25	18.2	47.8	29.7	21.4	1 1	0 0
HB-14M	12/9/89	30	25	0.42	17.9	34.2	27.6	13.4	6.8
HB-14D	1/24/89	30	40	251	40.0	45.9	13.2	0.8	0.0
HB-14D	1/25/89	30	40	199	43.4	45 0	10.8	0.8	0.0
HB-14D	2/28/89	30	40	170	6.4	44 3	40.4	8.1	0.8
HB-14D	12/9/89	30	40	44	14 3	40 7	36 2	7 7	1.1

Source: Johnson et al. 1991

Boiling Point Fractions. 1: methane - isopentane (<28°C)
2: isopentane - benzene (28 - 80°C)
3: benzene - toluene (80 - 111°C)
4: toluene - xylenes (111 - 144°C)
5: >xylenes (>144°C)

porting rod, such as a one-inch PVC pipe. Hinchee (unpublished data) has installed as many as 12 discretely-screened sampling points in a single 30 m (100 ft) boring. Collection of soil-gas samples under vacuum conditions is discussed in Subsection 3.3.4.2.

Figure 3.49
Typical Vapor Extraction Monitoring Point Construction Detail



Dimensions will vary for specific installations

3.6.5.2 Subsurface Vapor Phase Pressure Distribution

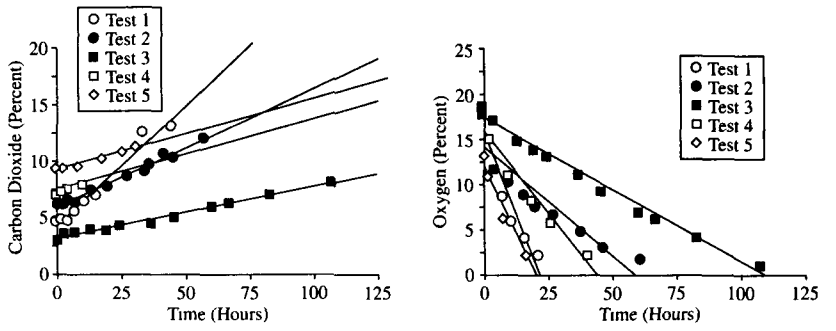
The installations used for soil-gas monitoring can also be used for subsurface vapor phase pressure monitoring. As in the case of field pilot-scale tests, these data can be used to assess the zone of containment of a vapor extraction-based system. In addition, the data can be used to estimate the subsurface pressure gradient and that estimate can be combined with permeability information to calculate vapor-flow rates through different soil zones (note that the absence or presence of a measured pressure does not indicate flow or remediation). Over time, changes in subsurface pressure distributions can indicate changes in other parameters, such as soil permeability. The practitioner should be equipped with a wide range of gauges, as pressures (vacuums) measured in extraction wells and subsurface monitoring points can vary from a few tenths of an inch to a few feet of water; injection pressures may be as high as several psi. The theoretical limit for vacuum measurements is ≈10 m (33 ft), but in actual practice, it is rare that a vacuum in the formation of more than 1.5 to 3 m (5 to 10 ft) of water is achieved.

3.6.5.3 Subsurface Respiratory Gas Monitoring

In bioventing or other vapor extraction-based systems the monitoring of subsurface respiratory gases (O_2 and CO_2) can be an important part of a vapor extraction-based process evaluation if the operator wishes to assess the contribution of microbiological degradation. To ensure maximum biodegradation, minimum oxygen levels of 2% to 5% v/v should be maintained throughout the formation (Miller 1990). Smith, Dupont, and Hinchee (1991) found that, although exhaust gas O_2 rose to 20% within 2 months of the initiation of venting, 6 months were required for O_2 to rise above 5% in some parts of the site.

Transient analyses of soil-gas samples can be used to estimate in situ biodegradation rates. These in situ respiration tests are conducted by shutting down the extraction system and measuring O_2 depletion and CO_2 production. Figure 3.50 (on page 3.129) presents plots of measurements. Consistent with figure 3.50, oxygen utilization appears to be constant (oxygen concentrations decrease linearly over time), based on the limited data published to date. Following are the steps in converting soil-gas oxygen depletion data to degradation rates:

Figure 3.50
Oxygen Utilization and Carbon Dioxide Production in Various Phases of a Bioventing Project at Tyndall AFB, Florida



Source: Miller 1990

1. Correct oxygen depletion for natural respiration from a "background" site (in practice, this background rate is very low, near zero, at most sites);
2. If data are linear and zero-order kinetics are assumed, calculate the slope of the O_2 concentration vs. time plot. The magnitude of the slope is defined to be k' (%/h);
3. Convert k' (%/h) to ((moles-O_2/m^3-vapor)/d) by using the Ideal Gas Law:

$$k'\left(\frac{moles-O_2}{(m^3-vapor)-d}\right)=\frac{k'(\%/h)}{100}24\left(\frac{h}{d}\right)\frac{P}{RT}\left(\frac{moles-O_2}{m^3-vapor}\right) \qquad [3.58]$$

where P (atm) denotes the total pressure in the subsurface (1 atm after extraction is terminated), R (m^3-atm/mole-K) denotes the universal gas constant (8.2 x 10^{-5} m^3-atm/mole-K), and T (°K) is the absolute temperature;

4. Divide k' ((moles-O_2/m^3-vapor)/d) by the stoichiometric ratio S (moles O_2/moles contaminant) to obtain the contaminant degradation rate k" ((moles-contaminant/m^3-vapor)/d):

$$k''\left(\frac{moles-contaminant}{(m^3-vapor)-d}\right)=k'\frac{\left(\frac{moles-O_2}{(m^3-vapor)-d}\right)}{S\left(\frac{molesO_2}{moles\ \ contaminant}\right)} \qquad [3.59]$$

For example, assuming the degradation of hexane (C_6H_{14}):

$$C_6H_{14}+\frac{19}{2}O_2\rightarrow 6CO_2+7H_2O \qquad [3.60]$$

then S = 19/2 moles of O_2 are consumed for each mole of hydrocarbon degraded; and

5. Convert to K ((g-contaminant/kg-soil)/d), the mass degradation rate of contaminant, normalized per unit mass of contaminant-containing soil, by multiplying k" by the molecular weight of contaminant MW (mg-contaminant/mole-contaminant), the vapor-filled porosity ε_A (m^3-vapor/m^3-soil), and dividing by the soil bulk density ρ_b (kg-soil/m^3-soil):

$$K\left(\frac{mg-contaminant}{(kg-soil)-d}\right)=k''\left(\frac{moles-contaminant}{(m^3-vapor)-d}\right)MW\left(\frac{mg-contaminant}{moles-contaminant}\right)$$

$$\varepsilon_A\left(\frac{m^3-vapor}{m^3-soil}\right)\div P_h\frac{kg-soil}{m^3-soil} \qquad [3.61]$$

This should be considered an estimate of biodegradation requiring numerous assumptions on the limited number of sites at which in situ respiration tests have been used to estimate biodegradation rates and at which soil hydrocarbon concentration reduction data was available, this estimate appears to be within a factor of 2 or 3 (Miller 1990; Downey 1993; Wilson 1994; and Hinchee 1994).

3.6.5.4 Soil Borings and Site Sampling

In many cases, collection and analysis of soil samples is required by regulatory agencies in order to demonstrate proof of remediation. Evaluation of process performance typically is based on limited initial and final soil samplings and, at times, on some intermediate sampling. The difficulty

in using soil sampling to evaluate the process lies in the extreme variability inherent in analyses of soils from a site contaminated by hydrophobic organics. Working at a hydrocarbon-contaminated site at Tyndall AFB, Florida, Miller (1990) established two treatment plots, each approximately 2.4 by 4.8 m (8 by 16 ft) in area and 1.5 m (5 ft) deep. Despite every effort to select uniformly contaminated plots, the 21 soil samples collected yielded coefficients of variation of approximately 100%. Prior to treatment of a JP-4 contaminated site at Hill AFB in Utah, Oak Ridge National Laboratory personnel analyzed 259 soil samples from the soils beneath a spill of 94,630 L (25,000 gal). The highest concentration exceeded 20,000 mg/kg and many samples had concentrations above 1,000 mg/kg. Of all the samples, however, only 77 (30%) showed contamination above detection limits. The point is, although soil sampling is an important part of verifying remediation broadly, soil sampling data must be carefully interpreted when used to quantitatively evaluate process performance.

3.6.5.5 Groundwater Sampling

Like soil sampling, groundwater sampling is often required to demonstrate system effectiveness. Many closure plans include some period of posttreatment groundwater monitoring (typically, one year) to demonstrate long-term effectiveness. Since the goal in many cases is to protect groundwater quality, there is reason to include groundwater sampling in monitoring plans. In processes aimed directly at treating the saturated zone (e.g., air sparging), these data are relevant in assessing system performance and assuring containment. Typically, the groundwater samples will be analyzed for selected contaminants and dissolved oxygen. In air sparging, some have used these data to assess the area being affected by sparging wells. It is assumed that elevated dissolved oxygen levels and decreased contaminant concentrations are indications that the sampling point lies within the zone of sparge-air flow. Great care should be taken in interpreting groundwater monitoring data, as monitoring wells are ideal short-circuiting pathways for both injection and extraction gas flow.

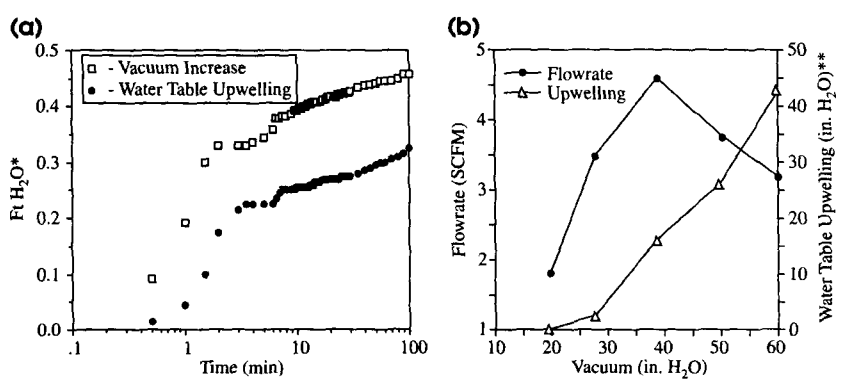
3.6.5.6 Water Table Fluctuations

It is well known that vapor extraction-based processes can induce significant water table elevation changes because of changes in the subsurface pressure. Figure 3.51 (on page 3.132) illustrates this phenomenon for a

vapor extraction system; in which it can be seen that water table elevation changes occurred in response to applied vacuum changes at an extraction well.

Water table fluctuations are important for at least two reasons. First, from a practical standpoint, it is possible for the water table to rise into an extraction vent and block or reduce airflow. In low-permeability soils, where higher vacuums may be required, this can be a serious limitation. Second, in rising, the water table may cover or mask some of the contaminated soil. This is particularly true for LNAPLs, such as a fuel hydrocarbons, which tend to spread on top of the water table. In many cases, changes observed in extracted contaminant vapor concentrations are the direct result of water table elevation changes; water table rises tend to correlate with decreases in contaminant vapor concentrations. Water table elevation changes may result from seasonal changes in precipitation, groundwater recovery process changes, or changes in other external pumping conditions (e.g., periodic use of a neighboring well). Obviously, mea-

Figure 3.51
Vapor Flowrate and Groundwater Upwelling Dependence on Applied Vacuum (a) and, Transient Watertable and Subsurface Vacuum Response (b) at a Vapor Extraction Application



* Ft H_2O denote vacuums expressed as equivalent water column heights
** Relative to level @ 20 in H_2O vacuum

Source: Johnson et al 1991

surement of water table elevations during the operation of vapor extraction-based processes is very important. See Subsection 3.3.4.5 for further discussion.

3.6.5.7 Tracer Gas Tests

Inert tracer gases (e.g., He and SF_6) can be used to gain a better understanding of the flow dynamics of vapor extraction-based processes. For example, a small quantity of tracer gas can be injected into the subsurface some distance from an extraction well, and its appearance at the extraction well can be monitored in order to assess the induced flow strength through the injection location.

Tracer gas tests are currently the best means to quantitatively assess flow dynamics, although Kerfoot (1992) has reported the development of an in situ tool that purportedly measures soil-gas velocities directly. The most valuable use of tracer gases at this time, however, is in the assessment of vapor extraction-based processes that involve air injection. As mentioned in Subsection 3.1.2, there is significant concern that improperly operated systems will accelerate the uncontrolled migration of contaminant vapors away from the treatment area. Tracer gas tests provide a simple and quick experimental means to define appropriate safe operating conditions for wells. They are conducted by mixing a tracer gas with the injection air stream and then monitoring it in the extraction system and near any sensitive vapor receptors (buildings, conduits, etc.). Injection and extraction rates are then modified until all of the tracer gas is recovered.

3.7 Technology Variations: Combined In Situ Soil Heating and Vapor Extraction

This monograph principally addresses soil vapor extraction and, to a lesser extent, the complementary technologies of air sparging and bioventing. In the authors' experience, these are currently the soil vapor extraction-based technologies most likely to be applied. There are, however, other vapor extraction-based technologies that deserve mention, technologies that combine in situ soil heating and vapor extraction.

Conventional vapor extraction equipment is combined with a means by which energy is supplied to the subsurface in order to elevate the subsurface temperature. This is done to broaden the range of applicability of vapor extraction-based technologies by enhancing either biological activity (through gentle heating to 30 to 40°C (86 to 104°F); see Subsection 3.2.12) or the rate of volatilization (through aggressive heating to >100°C (212°F)). As a general rule, biological rates are assumed to double for every 10°C (50°F) increase in temperature; nonetheless, of the two mechanisms, the potential for increasing removal by volatilization is much greater. This can readily be seen through an assessment of increases in pure component vapor pressures with equation [3.4] (see Subsection 3.2.2):

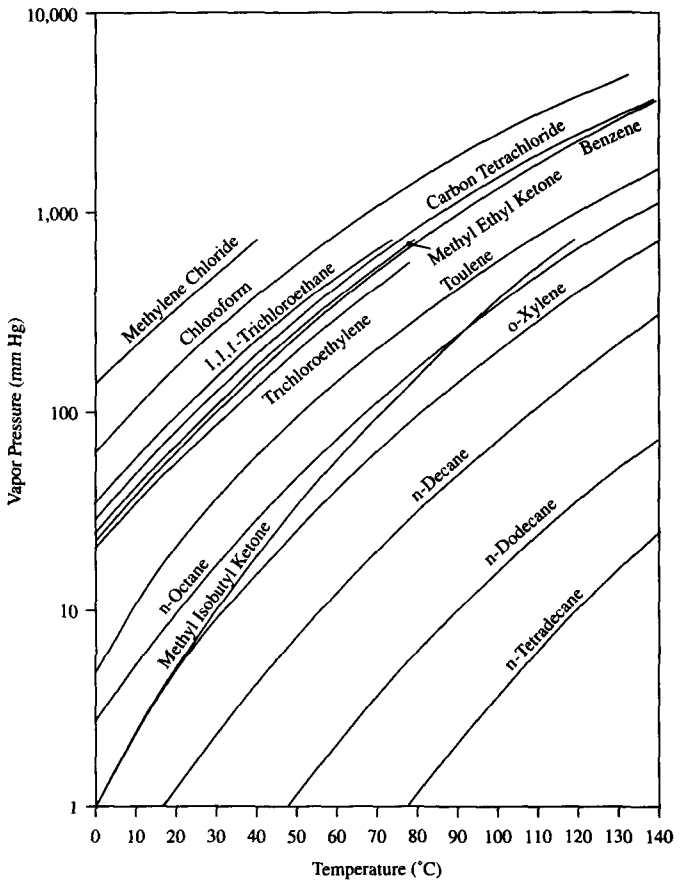
$$P_j^v = \exp\left(-\frac{\Delta H_v}{RT} + B_j\right) \qquad [3.4]$$

where ΔH_v is the molar heat of vaporization (cal/mole), R is the gas constant (1.99 cal/mole-°K), and B_j is a unitless constant. Values for ΔH_v can be found in standard thermodynamic tables (e.g., see Weast 1970); then, B_j can be determined by solving equation [3.4] for B_j at a known temperature and reference vapor pressure. Figure 3.52 (on page 3.135) shows the dependence of pure component vapor pressure on temperature for a range of hydrocarbons. If it is assumed that the soil can be heated to a given temperature, most of the screening models derived in Section 3.2 can still be used to estimate system performance. At a screening level, one can expect removal rates to increase in proportion to increases in vapor pressure.

In diffusion-limited formations, beneficial effects in addition to the vapor pressure increase result from increases in temperature. For an absolute temperature change from T_1 to T_2, vapor-phase diffusion coefficients increase roughly by the factor $(T_2/T_1)^{3/2}$, thereby helping to enhance the rate of vapor transport from low-permeability zones to regions of high-vapor flow. In addition, for temperature increases above 100°C (212°F), the production of steam from low-permeability, moist soils and its pressure-driven flow to regions of high-vapor flow can help drive contaminant vapors out of the low-permeability zones at a rate much higher than the natural diffusion rate.

To determine whether acceptable performance can be achieved at a given temperature, a heat input requirement is first calculated, realistic heat input rates are assessed, and the time required to achieve a target temperature is estimated. Sufficient energy must be supplied to heat the soil, raise the

Figure 3.52
Vapor Pressure for Various Organic Compounds as a Function of Temperature



Data from: Perry, Chilton, and Kirpatrick 1973; and Boublik, Fried, and Hala 1984.

temperature of the soil moisture and contaminants, cause the soil moisture and contaminants to volatilize, and then raise the gases to the desired temperature. In order to raise the temperature of dry uncontaminated soil from T_1 to T_2, the minimum energy input must be ΔH_s (cal/g-soil):

$$\Delta H_s = C_{p,soil}(T_2 - T_1) \qquad [3.62]$$

where $C_{p,soil}$ (cal/g-°K) denotes the mean heat capacity of the soil over this temperature range. Table 3.9 presents thermal data for various soils. If water is present in the soil, the temperature is elevated above the boiling point of soil moisture, and the process occurs at constant pressure, then the following additional energy input ΔH_w (cal/g-soil) can be approximated as:

$$\Delta H_w = \theta_w(C_{p,w-l}(T_b - T_1) + \Delta H_v + C_{p,w-v}(T_2 - T_b)) \qquad [3.63]$$

where θ_w (g-H_2O/g-soil), $C_{p,w-l}$ (cal/g-liquid-water/°K), ΔH_v (cal/g-H_2O), and $C_{p,w-v}$ (cal/g-water-vapor/°K) represent the soil moisture content, mean heat capacity of liquid water, heat of vaporization for water, and the mean heat capacity of water vapor, respectively. An equation similar to equation

Table 3.9
Thermal Properties of Selected Materials

	Porosity	Volumetric Wetness	Thermal Conductivity (10^{-3} Cal/cm sec-°C)	Volumetric Heat Capacity Cp (cal/cm^3-°C)	Source
Soils					
Sand	0 4	0 0	0 7	0 3	a
	0 4	0 2	4 2	0 5	a
	0.4	0 4	5 2	0 7	a
Clay	0 4	0 0	0 6	0 3	a
	0.4	0 2	2.8	0 5	a
	0.4	0 4	3 8	0 7	a
Peat	0.8	0.0	0 14	0 35	a
	0.8	0 4	0.7	0.75	a
	0.8	0.8	1 2	1 15	a
Miscellaneous Materials					
Water, liquid				1 0	b
Water, ice				0 45	a
Gasoline				0.76	b
Benzene				0.56	b
Kerosene				0.67	b
Wood				0 64-0.93	b
Air (dry at STP)				0 00028	b

Sources (a) Hillel 1982, (b) Perry, Chilton, and Kirkpatrick 1973

[3.63] can be formulated also for contaminants present (if they are solids at ambient temperature, heats of melting must be incorporated). An equation for heat required for air in the pore space can also be written, but this value will be negligible in comparison with the energy already required, as heat capacities of gases are much smaller than those of solids and liquids.

Given a total energy requirement, the minimum heating period duration can be estimated by simply dividing the total energy requirement ΔH_T (cal/g-soil) by the expected heating rate Q_H (cal/d). This value and an estimate of time for remediation at that target temperature are two quantities used to estimate the efficacy and cost of any in situ soil heating plan. In many of the heating methods described here, the rate of heating is likely to be the limiting step in remediation.

A number of thermal enhancement processes being used or under development are discussed below, and exhibit significant variations in heating rates, temperature limits, energy efficiency, complexity, and cost.

3.7.1 Steam Stripping

In situ steam stripping typically involves:

- delivering steam to the contaminated zone via injection wells;
- heating the contaminated zone to vaporize the contaminants or increase their mobility; and
- creating a pressure gradient to control movement of the contaminants and of the steam condensate front to a recovery point.

The injected steam travels some distance from the injection point and then condenses. The energy lost because of cooling and condensation is transferred to the formation. Contaminants in the soil may vaporize (due to increased vapor pressure), become dissolved in the condensate front (due to increased solubility), or be displaced (due to a reduction in viscosity and capillary forces). These processes must be controlled to minimize possible detrimental effects, such as contaminant "smearing" or enhanced vapor transport away from the source area.

In situ steam stripping may be successful where the organic contaminant consists of compounds with a low solubility in water and a boiling point below about 250°C (482°F) (Nunno et al. 1989; Murdoch et al. 1989). The process relies upon the same principles as conventional steam stripping in two-phase distillation. Contaminants are vaporized then condensed at the

steam front, and are often displaced as much as volatilized. They may be carried to the surface as a mixture of wet steam and organic vapor. A vacuum system collects the vapor mixture for removal of the organic contaminants. The water vapor is condensed, and the insoluble organic phase is collected for recycling or disposal. The offgas and water may be treated further to remove any remaining traces of organics.

In situ steam stripping requires steam generation and injection, vapor containment, and offgas collection and treatment system. The objectives of design of injection and extraction wells and process flow are to permeate the steam uniformly through the target zone, cause the condensate front to be driven to the extraction wells, and assure containment of vapor migration. Often, impermeable surface covers are used to help control the flow field.

3.7.1.1 Steam Stripping Technology

Three steam stripping methods have been used in field tests:

Method A – Steam injected into supply wells is drawn through the contaminated zone by vacuum;

Method B – Steam and hot air are injected from drill bits as the bits are rotated in the contaminated zone; and

Method C – Steam is injected below a bank of dense contaminant to lift it into a stream of hot water. The hot water is injected so as to move laterally over the bank of contamination in order to intercept the rising contaminant and carry it to a collection well.

Each method employs different injection and control techniques with the object of achieving acceptable contaminant removal along with efficient use of steam, given the combination of contaminants and geology at the site.

In Method A, steam injection wells are installed to inject steam at or below the level of the contamination. The wells are placed throughout the formation so as to fully saturate the contaminated area. Well spacing depends on the permeability of the formation. In field tests, well spacing of approximately 1.8 m (6 ft) has been used at sites having a variety of soils, including sandy silts, clay, and sand (Udell and Stewart 1989; Nunno et al. 1989). Steam pressure typically is about 40 kPa (6 psig) for well depths of approximately 6 m (20 ft). Pressures as high as 79 kPa (11.5 psig) have

been used in laboratory tests. The laboratory studies indicate better contaminant removal at higher steam pressure, if the pressures can be reached without fracturing the formation (Lord et al. 1990a & b). The contaminant can be withdrawn using vacuum extraction wells in the formation (Udell and Stewart 1989) or by applying a vacuum at the soil surface under a flexible membrane liner covering (Lord et al. 1990a & b) or a vacuum bell (Nunno et al. 1989).

Following are reported removal efficiencies under Method A:

- benzene, toluene, ethylbenzene, and xylene: 20% in clay and 99.5% in sand (Nunno et al., 1989);
- naphthalene: 60% in clay and 99.9% in sand (Nunno et al. 1989);
- polycyclic aromatic hydrocarbons: 35% in bog and 97% in sand (Nunno et al. 1989);
- phenol: 20 to 80% in clay or sand (Nunno et al. 1989); and
- acetone, xylene, ethylbenzene, and 1,2-dichlorobenzene: 98% (Udell and Stewart 1989).

Laboratory experiments have indicated that steam stripping efficiency may depend on the polarity of the compound as well as its vapor pressure (Lord et al. 1990 a & b).

Method B employs a process tower, which supports a pair of cutting blades at the end of a hollow shaft. The cutting blades are rotated in opposite directions as they are lowered vertically into the soil. The blades can reach depths of 9.1 m (30 ft). The cutting heads break up the soil and thereby assure the uniform flow of gases. Steam, at 200°C (392°F), and compressed air, at 135°C (275°F), are piped through the shafts to nozzles located on the cutter blades. A steel shroud (3.0 m (10 ft) by 1.8 m (6 ft) by 2.1 m (7 ft)) covers a 2.2 m (7.3-ft) by 1.2 m (4 ft) area of soil undergoing treatment. Larger areas are treated by multiple application of overlapping treatment blocks (La Mori 1989).

A blower keeps the shrouded area under vacuum in order to enhance the flow of gases from the soil and to prevent leakage to the outside environment. The offgases are passed to the treatment train where the water and organics are removed by condensation in coolers and treated in carbon adsorption beds. The air is filtered and recycled to the soil by a compressor.

Water is removed from the liquid stream by a four-stage separator followed by batch distillation and is then recycled to a cooling tower. The condensed organics are collected for recycle or disposal (La Mori 1989).

Removal of volatile organic compounds (EPA Method 8240) is reported as greater than 96%, with average pretreatment soil concentrations in the range of 1,114 to 3,954 mg/kg. Removal of semivolatile organic compounds (EPA Method 8270) is reported as ranging from 11% to 93%, with average pretreatment soil concentrations ranging from 1,014 to 12,116 mg/kg (La Mori 1989).

Method C is used to effect the contained recovery of oily wastes. Injection and production wells are drilled in a pattern designed to sweep oily waste accumulations with steam and hot water. Low-quality steam is injected below the deepest penetration of organic liquids. The steam condenses, causing an upward flow of hot water. The upward flow dislodges and sweeps organic liquids up into more permeable regions. Hot water is injected above the natural impermeable barriers heating and mobilizing the main accumulation of oily wastes. After organic liquids are mobilized above the impermeable barriers, hot water injection into and water withdrawal from the production wells are controlled so as to sweep accumulated oily wastes through the more permeable regions.

Oily wastes are contained vertically by controlling temperatures during hot water displacement. Downward penetration of oily wastes is reversed by the thermal expansion of the heated organic liquids. Flotation of the heated organic liquid phase is limited by injecting cooler water above the oily waste accumulations.

One-dimensional experiments showed a relationship between residual saturation of the oily contaminant and the temperature of the displacing hot water. As the sweep-water temperature increased from ambient to approximately 69°C (157°F), for tests without surfactant addition, the reduction in oily waste residual increased from less than 20% to more than 60% for soil with up to a nominal 3% by weight initial oily waste saturation. Under similar conditions, tests with surfactants increased the organic reduction to approximately 90%. Three-dimensional simulations were used to validate the operation of the cold-water cap and the displacement efficiencies shown in the one-dimensional tests (Johnson and Guffey 1990).

3.7.1.2 Advantages and Disadvantages of Steam Stripping

Because the petroleum industry uses steam injection for oil recovery, there is extensive experience with the technique. Steam injection can be applied to semivolatile as well as to volatile compounds. The organics can often be collected as a separate phase for reprocessing and reuse.

Depending on the extent of contamination, the amount of contaminant present, and formation characteristics, treatment times can be significantly reduced compared to those of ambient temperature treatment systems. Treatment times ranging from hours to days have been reported (La Mori 1989; Udell and Stewart 1989).

In impermeable formations, the steam flows may be too small to allow practicable treatment (Ghassemi 1988). Success of in situ steam stripping operations can also be limited where the formation or the contamination is heterogeneous. Interbedding of permeable and impermeable layers in the subsurface can lead to steam flow around the impermeable layers, rather than through them. Transport out of the impermeable regions is limited by the diffusion rate, which can be slow. Cyclic steam injection, however, can improve steam use efficiency in these cases (Udell and Stewart 1989; Briggs 1989). There is also concern about practical control of the steam condensate front in the absence of any lower confining unit; this front may contain, or displace, significant amounts of contaminant. If not properly controlled, the contaminant may be driven deeper, or become "smeared" throughout the subsurface.

Steam injection requires additional capital equipment and energy. This increases the cost and complexity over that of ambient temperature remediation systems. The high temperatures will also adversely affect biological degradation processes.

An inherent limitation of steam injection systems lies in their inability to heat formations to temperatures significantly greater than 100°C (212°F), as steam temperatures are limited by injection and subsurface pressures. Steam stripping may not be efficient for removal of higher boiling point compounds, such as some aliphatic and aromatic fractions of jet fuels and gasoline, chlorobenzene, trichloroethylene, dichloroethane, and tetrachloroethane.

3.7.2 Radio Frequency Heating

Radio frequency (RF) heating has the potential of increasing subsurface temperatures well above the 100°C (212°F) boiling point of water, allowing more rapid removal of higher boiling point compounds than does steam injection. Energy is delivered to the subsurface via radio-frequency waves, which excite molecular motion and induce heating (much in the same way a microwave oven heats food).

In addition to standard soil vapor extraction equipment, the system utilizes electrodes or antennae connected to a radio-frequency generator. These transmit radio-frequency waves into the formation where some of the energy is absorbed for heating. The exciter array electrodes can be inserted into holes drilled into the formation or positioned on the soil surface. A modified radio transmitter serves as the power source. The broadcast frequency is in the industrial, scientific, and medical band. Operating frequency is chosen based on the dielectric properties of the soil and the areal extent of the contamination.

RF heating occurs through ohmic and dielectric mechanisms. Ohmic heating results from a voltage drop pushing electrons up into the conduction band and moving them through the soil mass, producing resistance heating. For the most efficient and uniform heating with RF power, ohmic heat input should be kept to a minimum by limiting the induced voltage drop in the soil mass.

Dielectric heating results from distortion of the atomic or molecular structure in response to an applied electric field. Typically, the dipole moments of the molecules in a polar substance are randomly oriented. The application of an external electric field will cause the dipole moments to begin to align.

The dielectric constant is a critical parameter in RF heating system design. It is dependent on the moisture content of the soil. As formation heating proceeds, water is driven off, resulting in a drop in the loss tangent. Maintaining efficient coupling to the RF field with the formation when the moisture is removed is a major challenge in RF heating system design. Systems typically maintain coupling by changing the broadcast frequency, the electrical properties of the network used to match the exciter array to the soil mass, or both. Johnson, Otermat, and Chou (1991) describe a means for overcoming some of these problems by injecting a warm, moist vapor

stream across the target depth to maintain moisture (and hence, energy absorbance) in the target zone.

3.7.2.1 Status of RF Heating Technology

To the authors' knowledge, RF heating/vapor extraction has had limited field application. A number of laboratory-scale treatability tests have been conducted. The authors understand that the US Air Force Armstrong Laboratory Environmental Division, Tyndall AFB, Florida, plans a full-scale demonstration test in the future. (There have been field demonstrations of an RF process for enhanced recovery of oil from oil shale and tar sand deposits.)

A limited field-scale demonstration test was conducted at the Volk Air National Guard Base. The contaminated site had served as a fire-fighting training area for more than 25 years. Waste oils, fuels, and other hydrocarbons were burned in a flare pit to simulate aircraft fires. An estimated 189,000 L (50,000 gal) of hydrocarbon materials had migrated into the soil around the pit. During the test at this site, RF heating raised the soil temperature to 100°C (212°F) in 2 days and to 150°C (302°F) in 8 days. RF heating was applied for 12.5 days.

3.7.2.2 Advantages and Disadvantages of RF Heating

RF heating has potential as a soil heating method, as the user can potentially achieve more rapid heating rates and more uniform heating than with any competing technology. In addition, no fluid injection is required for heat delivery, and the entire system can be operated under vacuum conditions to insure containment.

Capital equipment costs (mainly the RF generator) currently appear to be limiting the development and application of this technology. For some large sites, it is possible that this technology may be cost effective; however, unless pilot-scale tests can be conducted with costs similar to those of competing technologies, it should not be considered seriously in remedial strategy planning. In addition, it must be noted that operation of this process requires a higher level of sophistication than most remediation processes.

As with other heating processes, the high temperatures will inhibit biological activity in the soil. High temperatures may also have an effect on

the soil structure and induce cracking, which may, however, present some advantages in low permeability formations.

3.7.3 Joule Resistance Heating

Another potentially efficient soil heating method uses the soil as the conduction path for electrical current. Energy lost due to electrical resistance heats the formation. A major challenge in using this technology lies in the inherent drop in electrical conduction with decreased soil moisture content. Because the current density is highest near the electrodes, soil in this area dries faster. As a result, the electrical resistance increases, and the heating rate decreases and becomes highly uneven (if voltage is held constant).

Permafrost has been melted prior to construction using in-ground resistance heaters ("conductive heating"; see Subsection 3.6.4). The efficiency of the method, however, declines as the volume melted increases, because of the increased path length for heat conduction. Maksimenko (1984) proposed a two-stage process using resistance heating to start the melting process and then applying the resistance heaters as electrodes in order to continue heating by electrical conduction through the melted permafrost.

One process specifically designed to remediate contaminated sites uses an array of conductors formed by inserting metal pipes into the contaminated soil (Heath 1990). An electrical current is passed between electrodes to heat the soil enough to remove most of the soil moisture and any volatile contaminants. Water vapor and volatile organics are collected by conventional vacuum extraction techniques. Heating and moisture removal also preconditions the soil by making it permeable to gas flow. The soil can be vented through the pipe-electrodes themselves. When the bulk of the soil moisture is removed, the voltage is increased to stimulate in-place oxidation of any nonvolatile organics. The process is reported to cleave the nonvolatile organics into smaller, lighter components, which then volatilize. The oxidation products are collected in the vacuum extraction system.

In situ vitrification (Koegler 1989; Buelt and Westsik 1987) also employs electrical conduction in soil but operates at temperatures high enough to melt the soil. To the authors' knowledge, this process has not been used with soil vacuum extraction, although a vapor shroud is employed at ground surface to collect any vapors driven upward by the heating.

3.7.3.1 Status of the Joule Resistance Heating Technology

A pilot test of in situ electrical heating of soil has been conducted in the field for permafrost melting. In-ground electric heaters melted permafrost to a radius of 2.3 m (7.5 ft) in 450 hours of heating with a specific power input of 27.4 kWh/m^3 (0.8 kWh/ft^3). Bench-scale studies of hazardous material destruction by electrical resistance heating are reported to remove 95% of 2-chlorophenol and 25 to 99% of a semivolatile/nonvolatile organic mixture. Sand, silty loam, and bentonite clay were used in the tests. Reportedly, the organics were partially volatilized and partially decomposed, producing peroxide in the presence of moisture and O_2^- by corona discharge in air.

To the authors' knowledge, joule resistance heating has not been used at field scale in conjunction with vacuum extraction. It is the authors' understanding that such field tests are being contemplated by Battelle's Pacific Northwest Laboratories, Richland, Washington.

3.7.3.2 Advantages and Disadvantages of Joule Resistance Heating

Joule resistance heating is an emerging and, as yet, unproven technology. As such, little information is available on its feasibility. Equipment costs appear high, at least of the same magnitude as for RF heating. The electrodes are thin rods or tubes that can be installed with little or no disturbance of the soil; thus, they are much easier to install than steam or hot air injection wells. Because the power source is electrical current, the equipment required for the supply of energy is typically less complicated than that used for steam generators, air heaters, or RF transmitters.

The key challenge in designing in situ joule resistance soil heating systems is to maintain uniform conduction through the soil mass during heating. Heating drives off soil moisture, thereby reducing conductivity, and causing uneven heating and inefficient use of electrical energy. This problem can be somewhat mitigated through electrode design and placement.

3.7.4 Conductive Heating

In conductive heating, a heat source is placed on the soil surface or inserted into the formation; the temperature of the heater is raised, and then the soil is heated by conduction. Although a number of heater designs are

possible, the most practicable is likely to be an off-the-shelf electrical resistance heater. Down-hole heaters are known to have been applied for the purpose of enhancing oil recovery, but their use for remediation is not widely reported. Johnson et al. (1992) describe a conductive heating soil vapor extraction process for the remediation of surficially-contaminated soils, which achieved a >99% reduction in chlorinated hydrocarbon concentrations in surficial (0 to 0.6 m (0 to 2 ft) BGS) soils (Johnson, unpublished data).

Conductive heating presents an advantage in that it is probably the least sophisticated heating technology discussed here. In addition, capital costs may be low in comparison with other methods described above, as electrical resistance heaters can be purchased off-the-shelf. A disadvantage is that heat conduction through soils is inherently very slow and large temperature gradients must be maintained to insure acceptable heating rates.

3.7.5 Modifying Soil Surface

Soil temperature can be affected by regulating the incoming and outgoing radiation, or by changing the thermal properties of the soil. Only relatively small temperature increases can be effected, but no auxiliary energy input is needed. For this method to be effective, surface modifications must increase the mean annual surface temperature. The problem lies in maximizing the flow of incoming solar radiation, minimizing the reflection and radiation of energy from the soil surface, and retarding or preventing heat losses to the atmosphere through conduction, convection, and evaporation.

The goals are to increase the heat absorption of the soil during warm or sunny periods and to reduce heat loss during cold or dark conditions. Simple approaches can be taken such as removing vegetation and/or tilling the surface, mulching with organic material or plastic sheeting, or irrigating in order to increase the heat capacity and thermal conductivity of the surface soil.

The simplest approach is to remove vegetation. A heavy mat of vegetation will absorb the solar radiation before it reaches the ground and thus reduce soil heating. In periods when the soil is emitting heat, however, the vegetation helps to insulate the soil and reduce heat loss. The net effect of removing vegetation is typically an increased average flow of heat into the soil; however, the competing effects result in reduced overall efficiency.

Greater efficiency can be obtained by using clear polyethylene sheets. The ground is covered with sheeting to increase radiation collection during the day and reduce convective and conductive heat loss at night. The relatively short-wavelength solar radiation readily passes through the clear plastic, but the longer wavelength radiation emitted by the soil does not. The most significant problems reported in the use of polyethylene are degradation of the material from exposure to cold and wind damage.

The soil can be irrigated to increase moisture content, thereby increasing the soil's thermal conductivity. The effect of the increase in thermal conductivity is somewhat offset by an increase in specific heat due to the water. Saturating soil with water, however, typically has the net effect of increasing the heat transfer rate. Irrigation has the least effect in peat and the greatest effect in sandy soils.

3.7.5.1 Status of Soil Surface Modification Technology

The technology of soil surface modification has undergone pilot-scale field testing in cold climates. Various surface treatments have been explored for applications in improving crop growth and melting permafrost in cold regions in tests unrelated to contaminated soil remediation. A literature search produced no reports indicating that surface modification to produce soil heating has been demonstrated for remediation of contaminated sites.

Clear polyethylene has been applied to increase soil temperature for improved seed germination (Dinkel 1966) at a site near Palmer, Alaska. This work demonstrated an increase of 16.7°C (62°F) at 2.5 cm (1 in.) depth in plots covered with clear polyethylene.

In a study of permafrost thawing (Nicholson 1978), soil temperatures were modified by removing vegetation to increase energy input in the summer and by adding snow fences to increase snow cover and improve insulation in the winter. Temperatures in the treated plot were significantly higher than in the control plot. Over the 5-year test period, the temperature at a depth of 10 m (33 ft) in the test plot rose from about -2.2°C (36°F) to about -0.4°C (32°F). Of particular note, the large drop in winter temperature was avoided. The winter temperature in the control plot at 0.25 m (0.82 ft) dropped to about -17°C (2°F), while the winter temperature in the test plot at 0.25 m (0.82 ft) only dropped to about -2°C (62°F).

Small plots were also used to test the effects of a variety of surface treatments. Soil temperature increases reported for the surface treatments were about:

- 2°C (62°F) with vegetation stripped;
- 4.5°C (40°F) clear polyethylene applied over natural vegetation; and
- 5.5°C (42°F) clear polyethylene applied over stripped soil.

Problems with polyethylene sheets — becoming brittle in winter cold and being easily destroyed by the wind — were noted. Dusting with carbon black and using a black dye reportedly delayed degradation.

Field tests of various surface treatments were also conducted at six test plots near Fairbanks, Alaska, from 1980 through 1983 (Esch 1984). Permafrost at the test site exceeded 30 m (98 ft) in depth, with an average temperature of -1°C (34°F) at a depth of 10 m (33 ft). The tests showed that simply stripping away the surface vegetation caused a drastic change in the energy balance of a previously undisturbed surface. Removing vegetation resulted in an increase in thaw depth of 2.0 m (6.6 ft) in 4 years. Light-colored gravel alone did not increase the thaw depth, but did improve control of vegetation regrowth. Gravel darkened with asphalt provided a thaw depth of 2.5 m (8.2 ft) in 4 years. Clear polyethylene film, applied just a few centimeters above the soil surface, increased the 4-year thaw depths by 15% when applied to a stripped soil plot, and by 17% when applied over an asphalt-coated gravel pad. Covering the asphalt-coated gravel pad with a clear polyethylene film to create a greenhouse effect resulted in an increase to 3.0 m (9.8 ft) thaw depth in 4 years.

3.7.5.2 Advantages and Disadvantages of Soil Surface Modification

Soil surface modification is a very simple technology that has the potential of supplying heat to depths of up to several meters at very low cost. It provides in situ bulk heating without requiring major external energy input or expensive capital equipment.

The low-energy density that is available limits the temperatures that can be achieved. Soil heating occurs through conduction from the surface downward. Thermal diffusivity of the soil is sufficiently low that temperature changes occur in a period of days or weeks. The method is most appli-

cable in improving biotreatment rates, particularly in cold climates. It is unlikely that application of this method would produce temperatures resulting in significant increases in the vaporization rate of water or stripping of contaminants.

3.7.6 Hot Air or Hot Gas Injection

Hot air injection can raise soil temperature; however, because of the very low heat capacity of gases, it has limited application. For example, air injection at a temperature of 100°C (212°F) into a sandy soil with a heat capacity of 0.5 cal/cm^3-°C (590 Btu/ft^3-°F) at a typical soil venting air-flow rate of 100 m^3/hr (50 ft^3/min) with a radius of influence of 8 m (26 ft), a 4-m-thick (13 ft-thick) soil column at 10°C (50°F), would warm at the average rate of approximately 0.15°C/day (32.3°F/day). As the soil warmed, the rate of warming would decrease. Generally, at the air-flow rates used in soil venting, air must be warmed to several hundred degrees centigrade in order to add sufficient heat to warm soils at a rate sufficiently high to be usable.

Hot gas injection appears particularly appealing when thermal treatment of offgas air is required. Hot offgas resulting from incineration represents wasted heat that potentially may be recovered by injection into the soil for use in removing contaminants. In a case reported by Oak Ridge National Laboratory (1990), the incinerator was distant from the gas injection wells, resulting in long piping runs and high-heat losses. If biodegradation is an important part of the treatment regime, the reduced oxygen content of the incinerator offgas could be a concern. Oxygen effects can be avoided by using an air-to-air heat exchanger. The heat exchanger transfers heat from the offgas to the, venting air while keeping the gases apart. The additional equipment required increases the system's complexity and cost and inevitably results in additional heat losses. Another significant problem may result when hot gas is used in attempting to warm soils for bioremediation; if gas temperatures rise more than 20 to 30°C (68 to 86°F) above ambient, microorganisms near the injection point may be inhibited or killed.

High temperatures help offset the low-heat capacity of the air, but create other problems. To carry significant amounts of heat in air, temperatures must be above 300°C (572°F). With these temperatures, substantial insulation may be required to control heat losses in the piping to the inlet well. Also, the high temperatures needed will damage the materials used in typical wells. In order to withstand elevated air temperatures and temperature

cycling, the wells require more expensive materials and more complex designs. Although not reported in the literature, the effects of high-air inlet temperatures and temperature cycling on conventional injection wells could pose problems. Steel pipe could be used in place of the more typical plastic piping. Even if steel injection wells are used, however, there would be another drawback. The bentonite, which seals most wells, would not maintain integrity at temperatures above 100°C (212°F). Cycling, that is, heating followed by cooling in a well, will result in substantial expansion and contraction of the well piping. A conventional concrete or cement seal could lose its integrity under these conditions. For substantial, long-term use of high-temperature air injection, new and much more costly injection well designs would likely be required.

Another heat source that has been used to generate hot air is solar heating. Under this concept, air is drawn through a flat-plate solar collector by a blower, which then discharges to an air injection well. The increase in air temperature imposed by the collector is limited. The system is reportedly used to increase the temperature to improve biodegradation rates (Billings 1991).

Hot air injection has been used in conjunction with steam heating to assure that the stripped organics remain in the gas stream. Two of the systems reviewed applied this technique — the Toxic Treatments - NovaTerra (USA), Inc., Detoxifier (La Mori 1989) and the ENSR groundwater cleanup system (Smith, Aiken, and Tursman 1990). Air injection in these systems, however, follows steam injection and its purpose is to maintain organics in the vapor state; hot air is not injected for bulk soil heating.

3.7.7 Fiber Optic Heating

The sun is a low-intensity source of energy for soil heating. Under ideal conditions the power density available from the sun is about 1 kWh/m^2 of collector. Parabolic collectors coupled to optical fibers are being tested for using solar energy to heat soil in situ (Houthoofd, McCready, and Roulier 1991). Collectors have been used in the past for direct heating of air and water. Significant heat losses during transmission may make this process undesirable for in situ heating of soil.

Compound parabolic concentrators, which have the advantage of collecting scattered sky light as well as direct sunlight, are modified for coupling to a cable of optical fibers. The optical fiber has the potential of transfer-

ring the solar radiation with high efficiency over long distances. Since the solar energy is conducted as light rather than as a hot fluid, thermal losses along the transmission line are greatly reduced. The collector surfaces would also remain relatively cool and radiate little energy because conversion to heat occurs at the radiator or at the end of the optic cable, rather than at the collector.

3.7.8 Warm Water Injection

Water has a much higher heat capacity than air. In soils sufficiently permeable to make water injection practical, warm water injection may represent a reasonable approach to increasing temperatures in order to increase biodegradation rates. At a site at Eielson Air Force Base, Alaska, encompassing an area of 230 m^2 (2,500 ft^2), water at a temperature of approximately 30°C (86°F) was injected at a flow rate of approximately 6 L/min (1.6 gal/min). Through the winter, soil temperature was maintained near 10°C (50°F) in the warmed area, and dropped below 0°C (32°F) in the unheated areas (Leeson et al. 1993).

The primary drawback of warm water injection lies in obtaining and delivering an adequate water supply. If permeability is low, the infiltration rates may be limited. In addition, water can be added only at temperatures below ≈100°C (212°F), limiting both heat input and the upper temperatures that can be obtained. Accordingly, warm water injection is probably not a practical approach to heating in order to improve volatilization rates for high-boiling point compounds.

3.8 Summary of Good Practices

Although soil vapor extraction is relatively well-developed, there are opportunities for significantly improving system performance and reducing costs. This is true because the state of the practice is largely empirically based and many common practices and beliefs have no apparent technical basis.

This section presents opportunities for improving soil vapor extraction system performance, but they are applicable to all vapor extraction-based processes. Similarly, the flow diagram in figure 3.53 (on page 3.153), the

current state of the practice of key elements which are addressed below, is generally applicable to all such processes, provided minor modifications are made.

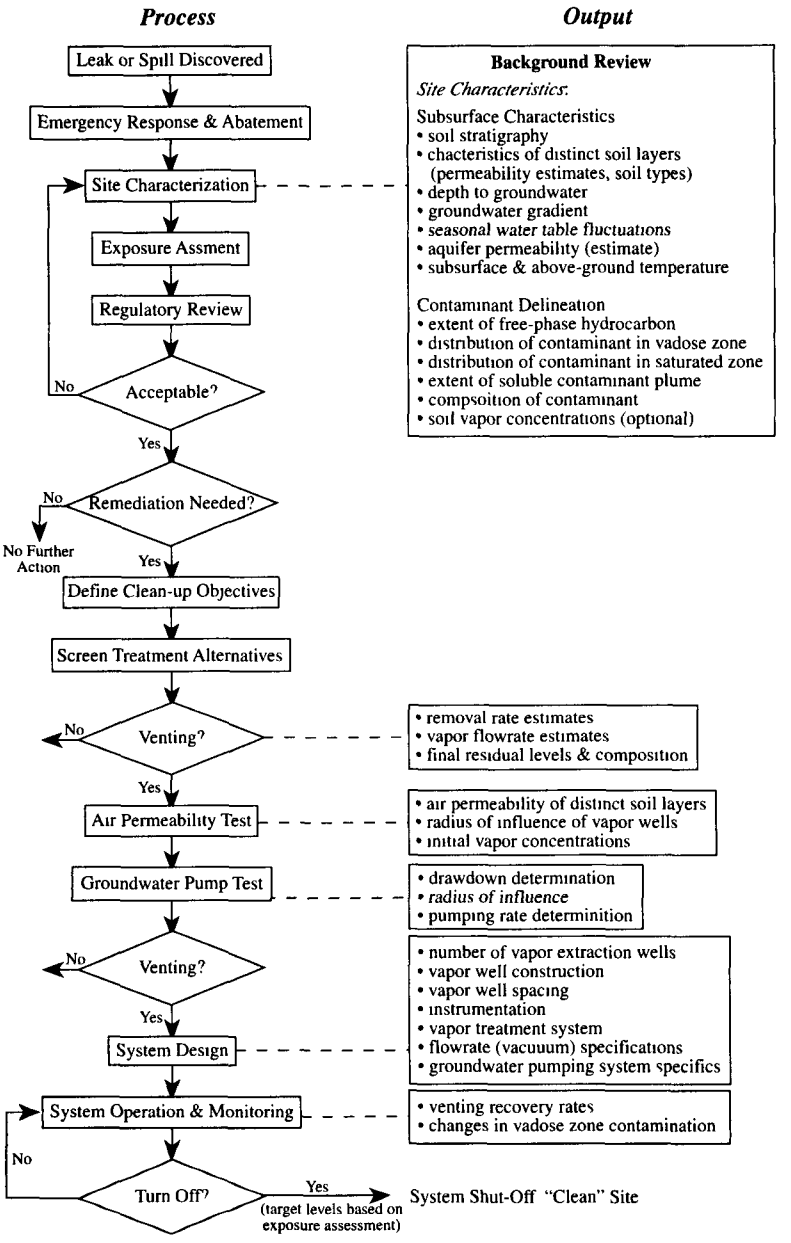
3.8.1 Site Characterization

Site characterization is performed in order to delineate the extent of contamination and identify potential migration pathways. In a basic assessment, soil cores are collected, groundwater monitoring wells are installed, and samples are taken. The soil and groundwater samples are analyzed in order to identify specific contaminants of concern and measure their concentrations. Sometimes, physical and chemical properties of the soils are also measured.

Too often site assessments are conducted without first determining data needs for the decisions to be made. Total project costs could often be reduced with a little preplanning. At many sites (e.g., sites of underground storage tank releases), the investigator has an idea of the contaminant source, contaminant type, and subsurface stratigraphy. At these sites, the following measures may lead to cost savings:

- At a minimum, sufficient data should be collected to enable drawing a subsurface cross-section map that identifies soil structure, contaminant distribution (levels and location), and the location of other significant features (groundwater table, tanks, subsurface conduits, etc.);
- If preliminary data indicate that vapor extraction may be applicable, soil borings drilled during the site assessment phase should be used for the installation of pilot-test vapor extraction wells and vadose zone monitoring point installations. Soil-gas samples can then be collected shortly after the basic assessment;
- Contaminants, especially complex mixtures, are more easily characterized by the distribution of compounds (e.g., boiling-point distribution) rather than by specific compound. Typically, as a result of regulatory requirements, soil samples are analyzed for a limited number of compounds of concern (e.g., benzene, toluene, xylenes) and some measure of total contaminant levels (e.g., total petroleum hydrocarbons). These data are often of

Figure 3.53
In Situ Soil Venting System Design Process



limited value in evaluating the applicability of vapor extraction-based processes and that of many other remedial processes;

- Field analytical methods should be used to supplement laboratory methods when possible. More data can be collected for the same, or less, cost; and
- Soil property analyses should be minimized. For each distinct soil layer, it is useful to have a measure of the moisture content, organic carbon fraction, and permeability. Laboratory physical property test results (i.e., permeability) should not be overemphasized because the tests are conducted on disturbed samples and the results are of limited value.

3.8.2 Defining Remedial Objectives

It is not uncommon for vapor extraction-based systems to be designed and installed without target cleanup goals being set. Consequently, closure requirements are often negotiated after prolonged operation of the system. In many cases, the additional operating time (and costs) yields no additional benefits, because inherent limitations of system or site condition (e.g., trying to remediate residuals trapped beneath the water table by soil venting alone). Therefore, to assure the least cost:

- Remedial objectives (target cleanup levels and duration of remediation) should be defined and constraints (costs, physical boundaries, community imposed, etc.) should be identified before remedial technologies are selected.
- Remedial objectives should be set with a view to protecting human health and the environment and be derived on a site-specific basis in consideration of reasonable potential beneficial uses.

3.8.3 Screening Treatment Alternatives

In the screening of treatment alternatives, all relevant factors, and not just the technical aspects should be considered. Vapor extraction-based technologies should be selected, of course, only if they are considered likely to meet the remedial objectives, given site-specific constraints. It is important to identify limitations and to assess the degree of uncertainty obtained in applying vapor extraction-based technologies. In some cases, a cost-

benefit analysis is useful. As demonstrated in Section 4.3, this requires tools to predict long-term system performance and costs. The availability and development of such tools are discussed in Subsection 3.8.7.

3.8.4 Field Tests

Currently, a typical vapor extraction field test is of short duration (a few hours). Competent practitioners measure flow rates, applied vacuums, and vapor concentrations at each extraction well. In addition, the subsurface pressure distribution away from the extraction well is also measured at a few locations. Often, to avoid the expense of installing test wells and vadose monitoring installations (which could have been installed during the site assessment as discussed above), existing groundwater monitoring wells are used. Consequently, pilot-test observations (flow rates, vapor concentrations, etc.) are often not representative of full-scale system performance. To generate more relevant data for full-scale system designs, it is important to insure that guidelines similar to those given in Section 3.3 are followed when conducting such field tests.

3.8.5 System Design

Designers need to recognize the inherent uncertainties associated with in situ remedial systems. Therefore, designs should be flexible enough to allow future system expansions and a range of operating conditions. This matter is discussed further in Section 3.8.7.

3.8.6 Operation and Monitoring

In practice, much of the monitoring of soil vapor extraction systems is driven by regulatory requirements. Typically, vapor extraction flow rates, system vacuums, and total contaminant vapor concentrations are measured on a periodic basis. In addition, permit conditions often require that emissions of specific compounds (e.g., benzene) be quantified and that vapor treatment unit performance be documented. But, monitoring plans are seldom designed with a view to optimizing system performance, the significant cost of remediation notwithstanding.

Monitoring plans should provide for measurements that yield sufficient information about system performance to enable process adjustments so that remediation can be optimized. As explained in Section 3.5, a wide

range of parameters can be observed at soil venting sites, yet the data typically collected in present practice can not be used to distinguish among several possible causes. For example, based on total hydrocarbon vapor concentrations, system performance data from diffusion-limited sites often resemble similar data from ideal sites; only if composition (e.g., boiling point distribution) data are collected can the cause affecting system performance be discerned.

3.8.7 Engineering Analysis

Engineering analyses are required to assess the feasibility of vapor extraction-based processes, interpret field-test results, design systems, and optimize system performance. To date, engineering analyses have usually been limited to determining the "radius of influence" R_I from pilot test data, drawing circles of radius R_I on a site plan map to determine well locations, and computing total hydrocarbon removal rates from vapor concentration and vapor flow rate data. The first two practices have no clear technical basis, and the third yields an incomplete picture of system performance. Yet, practitioners generally are not inclined to perform additional analyses. This may be because of the perception that: (1) engineering analysis, or "modeling," is a complex process that yields little return for the investment, (2) vapor extraction is a "forgiving" process in that any system, however poorly designed and operated, will eventually remediate a site if given enough time (and money), (3) vapor extraction is not competitive enough to bear the cost, or (4) site owners are not sufficiently informed of the need to provide an incentive to develop and utilize more sophisticated analyses procedures.

To understand the role of engineering analysis, consider the extreme case where no analysis is performed and systems are installed based solely on past experience. If the contaminant and site conditions are identical to another site that has been remediated, then reasonable confidence can be placed in expectations of system performance. If site conditions are similar, but not identical, predictions of system performance are less certain. With a new site that is dissimilar to any previous one, there is a high degree of uncertainty as to whether vapor extraction can successfully remediate that site. Rarely are identical sites encountered in practice; thus, there will always be a large degree of uncertainty when decisions are based on experience alone. Uncertainty about system performance means uncertainty about costs. Vapor extraction-based technologies can be costly, therefore, there is

a clear economic incentive to reduce the uncertainty in expectations/predictions of system performance.

Engineering analysis is the tool to help reduce uncertainty. It supplements field experience enabling the extrapolation of observations at one site in order to predict behavior at a dissimilar site, gain a better understanding of the parameters that most influence system behavior, and predict changes in system performance resulting from modifications of the system or changes in operating conditions. There is a wide spectrum of possible engineering analysis approaches ranging from the current approach generally applied (little or none) to the complex modeling of vapor flow and contaminant transport in the subsurface, such as that reported by Benson (1992). Because of costs associated with engineering analysis and the typical quality of site characterization data, it is unlikely that complex modeling will be routinely conducted for the majority of vapor extraction sites; however, there is an intermediate level of analysis that is justifiable by the potential for cost savings. Some examples are the site-specific flow modeling by Baehr and Hult (1991), screening/feasibility model development (Massmann 1989; Johnson, Kemblowski, and Colthart 1988; Johnson et al. 1990, 1991; Baehr, Hoag, and Marley 1989), and the use of models for "visualization" purposes (Wilson, Clarke, and Clarke 1988; Gannon et al. 1989; Mutch and Wilson 1990; Gomez-Lahoz, Rodriguez-Maroto, and Wilson 1991).

Another factor that may be limiting practitioners' use of engineering analysis is the lack of readily accessible computing tools. If programmed in a user-friendly manner, their use can minimize the time and costs of analyses. For soil venting applications, accessible predictive tools are presently primarily limited to air-flow models, such as CSUGAS (Sabadell, Eisenbeis, and Sumada 1988) and AIRFLOW (Joss and Baehr 1993a), and the screening-level flow, partitioning, and transport models such as HyperVentilate (Johnson and Stabenau 1991) (other models are currently available, but this Monograph does not provide provide an exhaustive listing or evaluation of each). For bioventing and air sparging, such tools are essentially nonexistent. The use of engineering analysis, or modeling, will likely increase in the future as additional computing tools become available.

4 POTENTIAL APPLICATIONS

Given enough time, vapor extraction-based technologies will "work" at any sites that yield air from the subsurface, because every contaminant incorporated in soil has a nonzero vapor concentration in the pore vapor space. Hence, as long as vapors are withdrawn from the subsurface, there is removal of contaminant. Additional measures, such as the enhancement to biodegradation resulting from increased oxygen supply rates, may act to accelerate the treatment process to some degree. Yet, there are bound to be constraints limiting the range of conditions under which vapor extraction-based technologies will be practicable. An attempt to define this range of conditions is made in this chapter.

4.1 Review of Reported Applications

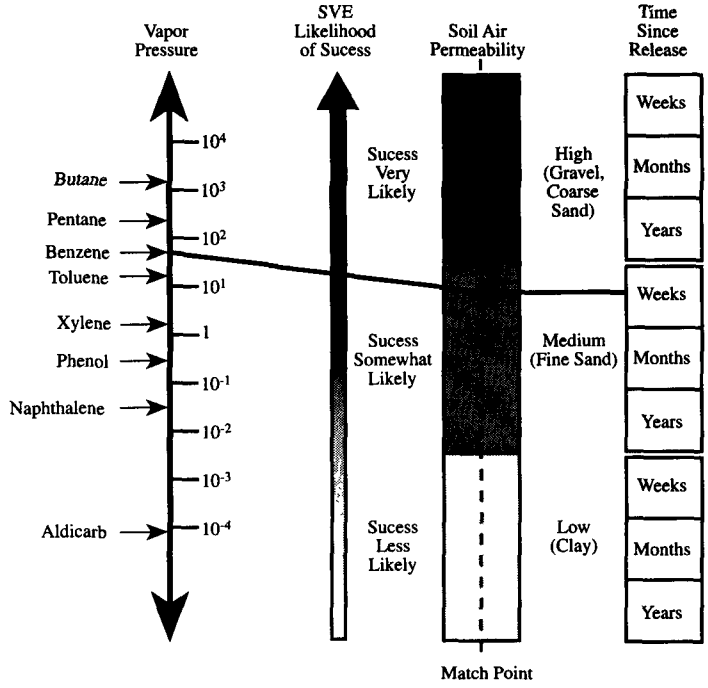
The first method for determining likely conditions is based on practical experience. Reports are gathered from pilot- and full-scale studies, and then the authors attempt here to correlate a relationship between the degree of "success" and geologic conditions, contaminant properties, and system variables (equipment, flow rates, etc.). This is similar to the approach taken by Hutzler, Murphy, and Gierke (1989) in defining the state of the practice for vapor extraction. The writers compiled a number of reports of applications and summarized information obtained from each. In reviewing this compilation and reports from other applications, it appears that vapor extraction is most often applied at sites where hydrocarbon fuels (gasoline, aviation fuels, etc.) and solvents have contaminated soils. Examples are service stations, electronics manufacturing sites, military bases, and dry cleaners. From the limited geological information documented, it appears that vapor extraction systems are often installed at sites with very permeable (sandy) soils. Beyond these observations, very little can be concluded from the documented applications. Most case histories fail to report final

soil and groundwater contaminant levels, costs, and original target cleanup levels; thus, it is difficult to judge whether or not the application was "successful." It should be noted that identifying unfavorable conditions for vapor extraction technologies based on these case histories is difficult, as they are biased strongly toward those sites where something significant occurred (rapid cleanup, high removal rates, etc.). To date, the engineered use of bioventing and air sparging has not been as extensive as that of vapor extraction; the few reported bioventing studies have been at aviation fuel (Hinchee et al. 1989; Miller et al. 1990) and "heavier" fuel releases (Downey and Guest 1991). Air sparging has been applied to remediate chlorinated solvents (Middleton and Hiller 1990; Bohler et al. 1990; Brown and Fraxedas 1991; Brown, Herman, and Henry 1991; Kaback et al. 1991), gasoline (Ardito and Billings 1990; Marley 1991; Kresge and Dacey 1991), and aviation gas (Griffin, Armstrong, and Douglas 1991).

4.2 Review of Recommendations

In the second method for determining conditions under which vapor extraction-based technologies will likely be applicable, the authors refer to the literature. Some writers define the range of applicability in terms of chemical properties; compounds with vapor pressures >0.5 mm Hg and dimensionless Henry's Law constants exceeding 0.01 are often considered candidates for vapor extraction (Hutzler, Murphy, and Gierke 1989). Brown, Herman, and Henry (1991) suggest that compounds with dimensionless Henry's Law constants $>10^{-3}$ are "strippable" and amenable to air sparging. In order to incorporate soil permeability as an additional criterion, others have resorted to the creative use of charts, tables, and nomographs (US EPA 1991a and b). Figure 4.1 (on page 4.3) is an example of one of the more informative representations of conventional thinking; the use of vapor extraction is recommended at "permeable" (sandy) sites contaminated by "volatile" compounds (gasoline, solvents, etc.), and its use is discouraged for less volatile compounds and lower permeability soils (clays). This guidance is clearly consistent with the case histories discussed in Section 4.1, above, as well as with basic vapor flow and contaminant partitioning considerations. Based on the limited data to date, it appears that this guidance is also roughly applicable to air sparging applications. For reference, soils with permeabilities to air flow exceeding 10^{-8} cm^2 (10^{-3} cm/s hydraulic conductivity) are commonly regarded as "permeable."

Figure 4.1
Soil Vapor Extraction Applicability Nomograph



Vapor pressure in mm Hg

Source: US EPA 1991a

4.3 Quantifying Applicability

In summary, based on case studies and published guidance, vapor extraction-based technologies are likely to be most successful at sites where volatile compounds have impacted permeable soils. It is important to note, however, that this guidance is only intended to roughly define the range of applicability, and not to limit it. Obviously, other equally significant factors such as contaminant distribution, remedial objectives, economics, equipment availability, community pressures, and physical boundaries are neglected in this initial evaluation of applicability. Having recognized this, other investigators are focusing on the development of methods incorporat-

ing all relevant parameters in order to determine applicability on a site-by-site basis. These efforts typically involve a quantitative prediction of long-term system performance based on site characteristics, contaminant properties, and pilot-scale data. For example, Johnson et al. (1990) and Johnson and Stabenau (1991) compare remedial objectives (cleanup levels, time to achieve cleanup) with screening level predictions of system performance in order to determine vapor extraction applicability. This approach was illustrated in Subsection 3.4.7. Accepting the uncertainties associated with screening-level predictions, the major deficiency of the approach outlined by Johnson et al. (1991) is the failure to explicitly incorporate economic constraints. A more general method for quantitatively defining the range of potential applications for vapor extraction-based technologies is described below and then illustrated through a simplistic example.

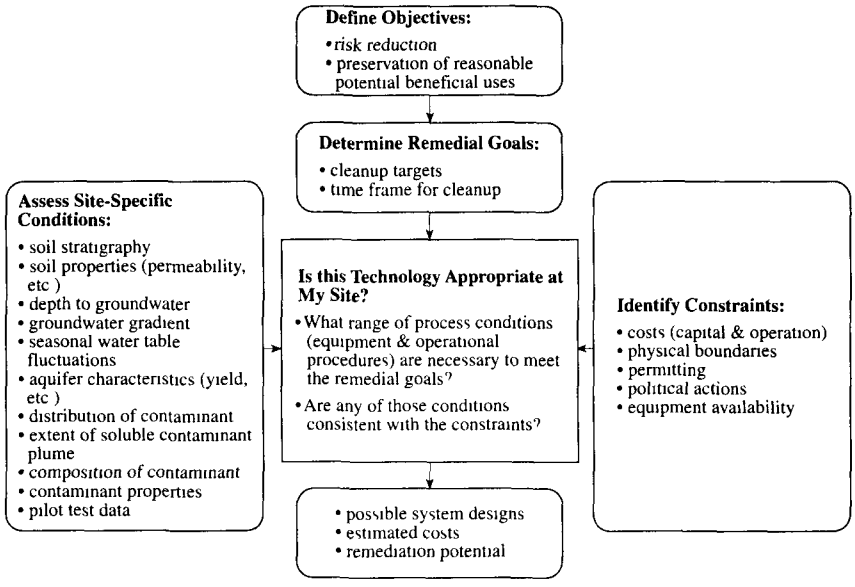
Figure 4.2 (on page 4.5) outlines one process for determining the applicability of vapor extraction-based technologies. A vapor extraction-based technology is potentially applicable, of course, if remedial goals can be met given constraints imposed at the site. The remedial goals include target cleanup levels and an acceptable time frame for remediation and are based on considerations of risk-reduction and preservation of reasonable potential beneficial uses. Site-specific data, including geological conditions contaminant characteristics are also required and pilot test data are considered, if available. Typical constraints include total project cost, permitting requirements, physical boundaries, community-imposed limitations, and equipment availability.

Given the necessary inputs, the objective is to determine whether there are technically feasible process configurations and operating conditions that will satisfy both the remedial goals and imposed constraints. Therefore, a tool is needed to accurately predict the performance and costs of a given system. Unfortunately, under the current state-of-the-practice, such predictive tools are not accessible to most practitioners (see Section 3.8.7 for discussion). Therefore, a screening level analysis is presented here to illustrate the benefits of the general approach outlined in figure 4.2 (on page 4.5). In this example, the authors evaluate the applicability of vapor extraction for the remediation of an operating service station and, for this purpose, collected the following data and information:

Site characterization data:

- Based on inventory records 22,700 L (6,000 gal) of regular gasoline have leaked from an underground storage tank;

Figure 4.2
Applicability Decision Process



- Free-product skimmer pumps have recovered 3,785 L (1,000 gal) of gasoline floating on the water table;
- Soils between the release point and groundwater are composed of fine and silty sands; and
- It is anticipated that a groundwater pumping system will have to be installed along with any vapor extraction system in order to counteract the upwelling induced by the vapor extraction wells.

Remedial goals and economic constraints:

- Achieve a 90% reduction in total gasoline levels and reduce benzene levels in soils so that groundwater cleanup standards (based on preservation of reasonable potential beneficial uses) are met;
- Effect remediation within a 20 year period; and

- Projected cost of vapor extraction must be less than $500,000, which is the total cost estimated for an alternate excavation and disposal option.

Design considerations:

- Based on screening-level analyses, it is estimated that in order to achieve the desired reduction in gasoline and benzene levels, a minimum of 100 L-air/g-gasoline must flow through the zone of contamination. Given that a significant fraction of the residual is located near the water table, an efficiency factor of 20% is assumed. Thus, the screening-level analysis is based on a vapor requirement of 100/0.2 = 500 L-air/g-gasoline (see Johnson et al. 1990, Johnson and Stabenau 1991 for more details on the screening analysis);
- A pilot test was conducted using an existing groundwater monitoring well and it is estimated that the maximum practicable vapor-flow rate from vapor extraction wells is 9.5 L/sec (20 standard ft^3/min); and
- Local air emissions requirements mandate a 90% reduction in total hydrocarbon concentration of extracted vapors prior to discharge.

Economic analysis (all costs given in current $):

- There will be a minimum installation cost of $20,000;
- Cost for vacuum pump/blower is $5,000 per 47 L/sec (100 standard ft^3/min) capacity;
- Installation cost for vapor extraction wells is $5,000 per well;
- Cost for vapor treatment is $100,000 per 230 L/sec (500 standard ft^3/min) capacity;
- Operation & maintenance costs are estimated to be $15,000 per year; and
- All costs quoted above include piping and miscellaneous expenses.

Based on the above information, the next step in the applicability analysis is the calculation of the number of wells, N_{wells}, required based on the 500 L-air/g-gasoline vapor requirement. If:

M_R = mass of residual gasoline in soil = 1.5 x 10^7 g = 5,000 gal
Q_{well} = flow rate to a single well = 9.5 L/sec = 20 standard ft^3/min
τ = time period for remediation; $0 < \tau < 20$ years
α = vapor volume requirement = 500 L-air/g-gasoline

then the required number of wells is related to these other parameters by:

$$N_{wells} = \frac{\alpha M_R}{Q_{well}\tau} \qquad [4.1]$$

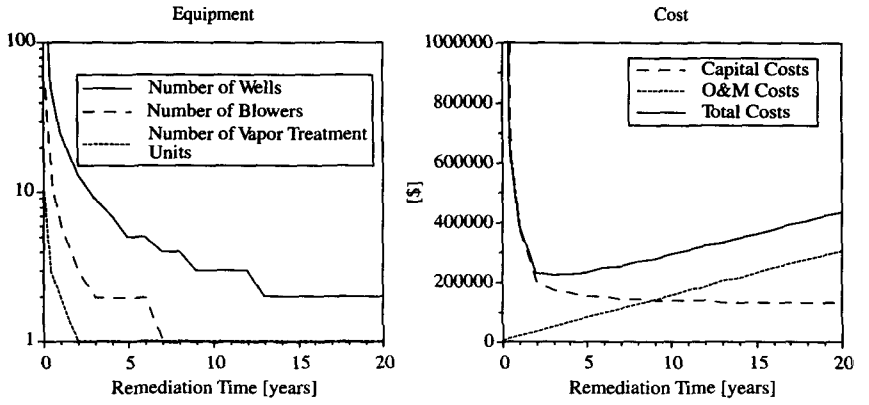
where the value N_{wells} is rounded up to the next largest integer (i.e., N_{wells} = 2.3 is rounded up to N_{wells} = 3). The estimated total cost of remediation by vapor extraction is then:

Cost = \$20,000 (minimum installation cost)
+ \$5,000 N_{wells} *(extraction well installation)*
+ \$5,000 $N_{blowers}$ (blower/vacuum pump cost)
+ \$100,000 N_{VT} (vapor treatment unit cost)
+ \$15,000 τ (operation & maintenance costs) [4.2]

where the number of blowers, $N_{blowers}$, and the number of vapor treatment units N_{VT} are based on the total system flow rate and their individual capacities (i.e., 47 L/sec (100 standard ft^3/min) for blowers, 236 L/sec (500 standard ft^3/min) for vapor treatment units).

Figure 4.3 (on page 4.8) displays results of this screening analysis, equipment required, and associated costs with different remediation periods. For short remediation times (<2 years), the total cost is dominated by capital equipment costs associated with the large number of wells, blowers, and vapor treatment units required. For longer remediation times, capital equipment costs are relatively constant, and the increase in total cost with increased remediation time is due to increased total operation and maintenance (O&M) costs. It should be noted that the shape of the total cost vs. remediation time curve shown in figure 4.3 is similar to curves that would be generated from more detailed analyses. There is typically an optimal design remediation time corresponding to the minimum total cost. In figure 4.3, the minimum total remediation cost is ≈\$200,000, which corresponds to systems designed for 2 to 4 year remediation durations. In this example, therefore, vapor extraction is judged to be applicable because the estimated total cost associated with it is less than the cost of the excavation and disposal option.

Figure 4.3
Results of Applicability Screening Analysis



However simplistic, this example illustrates the importance of incorporating all relevant factors into the applicability screening analysis. Had the desired time frame for remediation been less than a year or had there been options having total estimated costs significantly less than $200,000, vapor extraction would have been judged not to be applicable, despite the fact that the contaminant is "volatile" and subsurface soils are "permeable." The results of this analysis also hint at some of the benefits of air sparging and bioventing. Air sparging is expected to lower remediation costs where residuals trapped within or beneath the groundwater capillary fringe zone contribute to unacceptable groundwater concentrations; capital equipment and operational cost savings are realized because groundwater pumping systems are not required to lower the water table and expose soils for vapor extraction and long-term operating expenses are reduced because the time frame for remediation is shortened. Engineered bioventing systems offer capital equipment cost reductions by eliminating vapor treatment equipment, the need for an explosion-proof blower, and reducing the blower size. In a bioventing operation, lower air-flow rates frequently reduce operation, monitoring, and maintenance costs on a daily basis, but they can increase the time required for cleanup. The net impact on cost depends on site-specific factors.

5

PROCESS EVALUATION

Throughout this monograph the authors stress that the practicable degree of remediation through vapor extraction-based processes is limited by site characteristics and contaminant properties. The actual degree of remediation achieved, of course, also depends on specific skill and knowledge of the practitioner, which is reflected in the system design and operation. Unfortunately, even very inefficient remedial processes may appear to be highly successful in the eyes of less-informed practitioners.

At this point, it would be useful to present a tabulation of case study results clearly showing the demonstrated capabilities of vapor extraction-based processes. Review of available data, however, shows that most case studies are merely expositions of anecdotal data and pseudo-science that add very little to basic knowledge of vapor extraction-based processes. Buscheck and Peargin (1991) surveyed 143 vapor extraction projects in an attempt to correlate performance with relevant parameters and concluded that the majority of sites were insufficiently monitored to provide useful information. For this reason, the authors choose not to present such a tabulation, as they feel the results can be very misleading. Instead, they incorporate results of studies throughout the text to illustrate key concepts.

Following are the two key questions that generally are not answered in case studies:

- What triggered the decision to turn the system off?; and
- Were the cleanup goals achieved (what was the condition of the site after treatment)?

In practice, it is not always apparent from process monitoring when a vapor extraction-based system has achieved its cleanup goals. Some vendors claim vacuum extraction cleanups at some sites in fewer than 90 days. Dupont, Doucette, and Hinchee (1991) report completion of a combined vacuum extraction/bioventing remediation of a jet fuel-contaminated site in

about 2 years. Based on the authors' experience, most systems installed at service stations operate for periods greater than one year and less than five years; this is supported by the survey reported by Buscheck and Peargin (1991).

Ultimately, soil sampling is often required to verify cleanup and in many cases some residual hydrocarbons are detected. To avoid the cost of premature sampling, a pragmatic approach is to operate the system until both the contaminant and the respiratory gas concentrations approach background levels, no significant restart spike is observed, and oxygen utilization does not exceed background. These conditions indicate that the vacuum extraction system has accomplished all it can, and that either the site is clean or the residual contamination is not responding to vacuum extraction treatment.

It is also possible to define an end point based on economic analysis. As mentioned in Section 3.5, the cost-effectiveness of an extraction system can be tracked over time, and the decision to cease operation can be pegged to a given cost per unit contaminant removed.

6
LIMITATIONS

By examining the data from the available laboratory-, pilot-, and full-scale studies and reviewing the conditions that affect the range of applicability and methods used to decide applicability (see Section 4.1 through 4.3), one can begin to understand some of the limitations of vapor extraction-based technologies. Table 6.1 (on page 6.2) summarizes a number of scenarios in which the chances of conducting "successful" vapor extraction-based remediation are diminished. In most of these scenarios there is a condition that limits the rate of remediation (e.g., soil permeability or soil heterogeneity), or affects design (e.g., shallow water tables or strict air emission requirements). Thus, in these scenarios, vapor extraction-based processes may not be cost competitive with other remedial options.

In addition, there is a limitation common to all in situ technologies. Given the information available from typical site characterization efforts, systems are selected, designed, and operated under conditions of considerable uncertainty. Thus, there is no guarantee that any in situ process will perform as expected, even under seemingly ideal conditions. To some degree, the effect can be minimized by incorporating some factor for uncertainty into the analysis and by designing flexible systems that can be expanded and operated over a range of conditions.

Table 6.1
Limitations of Vapor Extraction-Based Processes

Scenario	Processes Affected	Limitations
desired remediation time is short (<6 months)	vapor extraction, air sparging, bioventing	most economically-feasible vapor extraction-based system designs achieve remediation in 0.5 - 3 year time frame
subsurface soils are highly heterogeneous with large air permeability contrasts, or soils are fractured	vapor extraction, bioventing	remediation rate is likely to be limited by mass transfer rates (diffusion-controlled), air-flow path is difficult to control
subsurface soils are highly heterogeneous with large air permeability contrasts, or soils are fractured	air sparging	injected air-flow path is difficult to control
residual contamination is located in the groundwater capillary fringe	vapor extraction, bioventing	may be difficult to extract vapors and deliver O_2 without causing groundwater upwelling to saturate contaminated zone, groundwater drawdown system may be required
contaminant does not partition well to vapor phase (i e , vapor pressure <1 mm Hg, or dimensionless Henry's Law constant <0 001)	vapor extraction, air sparging	volatilization removal rates will be low, unless extracted/injected vapor flow rates are very high, will be difficult to reach soil cleanup levels <1 mg/kg
soil is not very permeable to air-flow (i.e., permeability $<10^{-9}$ cm^2)	vapor extraction, air sparging	volatilization removal rates will be low, unless vapor concentrations are very high
soil is not very permeable to air-flow (i e., permeability $<10^{-11}$ cm^2)	bioventing	oxygen delivery (and biodegradation) rate will be low
compound is resistant to biodegradation	bioventing	low biodegradation rates
very little above-ground surface area available	above-ground vapor extraction, above-ground bioventing	above ground processes require dedicated area for duration of remediation (often >3 months)
shallow (<5 ft BGS) contamination	vapor extraction, bioventing, air sparging	"radius of influence" of vapor extraction wells is small, economics may favor other options (i.e., excavation & disposal)
shallow groundwater (<5 ft BGS)	vapor extraction, bioventing, air sparging	"radius of influence" of vapor extraction wells is small, economics may favor other options (i.e., excavation & disposal)
very strict air emissions requirements	vapor extraction, air sparging, bioventing	vapor treatment costs can make vapor extraction uneconomical relative to other options

BGS - Below Ground Surface

7

TECHNOLOGY PROGNOSIS

Currently, there are few effective in situ processes for treating soils contaminated with volatile components, and soil vapor extraction continues to be the preferred option for treating soils contaminated by fuel tank releases. Similarly, there are few alternatives to air sparging for residuals trapped below the water table and to bioventing for treating less-volatile biodegradable compounds. Of the vapor extraction-based technologies, soil vapor extraction is the most fully developed, having been practiced longest and at the largest number of sites. Results from laboratory and modeling studies have helped develop a basic understanding of the processes affecting soil vapor extraction system performance. There are, nonetheless, identifiable needs for further development and demonstration, discussed in Section 7.1 (see Section 3.8 for recommendations for improving the state of the practice of soil vapor extraction). Air sparging and bioventing, on the other hand, are promising developmental technologies and a niche has been identified for each. Needs for further development and demonstration are discussed in Sections 7.2 and 7.3. Other vapor extraction-based processes, such as in situ soil heating, should be considered experimental at this time.

7.1 Soil Vapor Extraction

Although this section addresses soil vapor extraction, it applies to all vapor extraction-based processes.

Under the current state of the practice, systems are designed based on the "radius of influence" calculated from pilot-test data (this is an extension of groundwater "capture zone" design practices). A serious defect in this approach is that systems are designed without considering remedial objectives, especially time and cost. Although a poorly designed system may

eventually remediate a site, the cost will likely be substantially increased. While appealing in its simplicity, the radius of influence approach has no technical basis, and there is no obvious relationship between the radius of influence (as it is commonly defined by subsurface pressure distributions) and the zone of soil remediated by a vapor extraction well in a given period, as illustrated by Johnson and Ettinger (1994). Thus, there is a need for design methods to incorporate long-term system performance predictions, remedial goals, economic, and other considerations.

To cost effectively operate a vapor extraction-based system, one must have a good understanding of induced vapor-flow patterns in the subsurface. Vapor-flow patterns are deduced from subsurface pressure measurements, knowledge of the site stratigraphy, hydrogeology, and vapor-flow models. It would be useful to have practical devices that directly measure vapor-flow paths and flow velocities in situ, such as that described by Kerfoot (1992).

When vapor treatment is required, it is often a significant part of total vapor extraction system costs. Presently, most vapor treatment units (e.g., thermal oxidizers, catalyst beds, and internal combustion engines) combust vapors; however, lower cost, noncombustion alternatives, including biodegradation- and absorption-based processes, are being evaluated.

Another factor that may be limiting practitioners' use of engineering analysis (see Subsection 3.8.7) is the lack of readily accessible computing tools. If programmed in a user-friendly manner, their use can minimize the time and costs of analyses. For soil venting applications, accessible predictive tools are limited primarily to air-flow models, such as CSUGAS (Warner et al. 1991) and AIRFLOW (Joss and Baehr 1993a), and the screening-level flow, partitioning, and transport models, such as HyperVentilate (Johnson and Stabenau 1991). For bioventing and air sparging, such tools are essentially nonexistent. The use of engineering analysis, or modeling, will likely increase in the future as additional computing tools become available.

7.2 Air Sparging

As observed in Subsection 3.1.2, considerable research and demonstration must be conducted before a consistent and reliable design approach will be realized. To date, limited information exists on the assessment, monitoring, performance analysis, modeling, and engineering design necessary to implement air sparging with confidence and predictability. With proper assessment, design, and operation, however, air sparging may become a powerful remedial technology. Its potential for circumventing the need for prolonged groundwater pumping systems certainly makes it attractive.

The effectiveness of air sparging is dependent upon how well the injected air travels through the saturated zone. Although there is a large body of literature focused on multiphase flow (e.g., air and water) there is currently little practical understanding of how these processes influence the range of behavior likely to occur in porous media at air-sparging sites. As a result, many air-sparging systems are being installed on a trial-and-error basis. To accelerate the development and understanding of the capabilities of this process, the following are needed:

- a better understanding of the distribution of air resulting from subsurface injection and how it is affected by soil structure and process variables;
- measuring devices to help better delineate the effect of an air-sparging well at a given site;
- guidelines for applicability and field testing based on fundamental considerations; and
- well-documented studies illustrating the performance and long-term impact of air sparging at a number of sites.

It is also important to note that, as explained in Subsection 3.1.2, air is being forced into the subsurface and the possibility of vapor migration to nearby buildings or utility corridors is a concern. Thus, it would be useful to have a monitoring method that insures proper control of vapor-flow paths.

7.3 Bioventing

Like air sparging, bioventing is also a developing process, and many questions remain unanswered. Following are some that need to be addressed:

- What situations are amenable to biodegradation?
- What range of biodegradation rates can be achieved in the field?
- Are O_2/CO_2 vapor concentrations reliable indicators of biodegradation? and
- What is the most cost-effective practice of the process?

A

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* U.S. GOVERNMENT PRINTING OFFICE: 1995-620-508/82045