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INNOVATIVE SITE REMEDIATION TECHNOLOGY

DESIGN & APPLICATION

Volume 7

Vacuum Extraction and Air Sparging

Prepared by the American Academy of Environmental Engineers under a cooperative agreement with the U.S. Environmental Protection Agency

THE WASTECH® MONOGRAPH SERIES (PHASE II) ON INNOVATIVE SITE REMEDIATION TECHNOLOGY: DESIGN AND APPLICATION

This seven-book series focusing on the design and application of innovative site remediation technologies follows an earlier series (Phase I, 1994-1995) which cover the process descriptions, evaluations, and limitations of these same technologies. The success of that series of publications suggested that this Phase II series be developed for practitioners in need of design information and applications, including case studies.

WASTECH® is a multiorganization effort which joins 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, the Soil Science Society of America, and the Water Environment Federation, together with the American Academy of Environmental Engineers, the U.S. Environmental Protection Agency, the U.S. Department of Defense, and the U.S. Department of Energy.

A Steering Committee composed of highly respected members of each participating organization with expertise in remediation technology formulated and guided both phases, with project management and support provided by the Academy. Each monograph was prepared by a Task Group of recognized experts. The manuscripts were subjected to extensive peer reviews prior to publication. This Design and Application Series includes:

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INNOVATIVE SITE REMEDIATION TECHNOLOGY: DESIGN AND APPLICATION

VAPOR EXTRACTION and AIR SPARGING

One of a Seven-Volume Series

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The panel that reviewed the monograph was reviewed by a panel comprised of the Project Steering Committee, Chaired by Peter W. Tunnicliffe, P.E., DEE, Camp Dresser & McKee Inc.

management and remediation industry.
HWAC's mission is to serve and

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REVIEWING ORGANIZATIONS

The following organizations contributed to the monograph's review and acceptance by the professional community. The review process employed by each organization is described in its acceptance statement. Individual reviewers are, or are not, listed according to the instructions of each organization.

Air & Waste Management Association

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.

Qualified reviewers were recruited from the Waste Group of the Technical Council. It was determined that the monograph is technically sound and publication is endorsed.

The lead reviewer was:

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American Society of Civil Engineers

The American Society of Civil Engineers, established in 1852, is the premier civil engineering association in the world with 124,000 members. Qualified reviewers were recruited from its Environmental Engineering Division.

ASCE has reviewed this manual and believes that significant information of value is provided. Many of the issues addressed, and the resulting conclusions, have been evaluated based on satisfying current regulatory requirements. However, the long-term stability of solidified soils containing high levels of organics, and potential limitations and deficiencies of current testing methods, must be evaluated in more detail as these technologies are implemented and monitored.

The reviewers included:

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Hazardous Waste Action Coalition

The Hazardous Waste Action Coalition (HWAC) is the premier business trade group serving and representing the leading engineering and science firms in the environmental management and remediation industry. HWAC's mission is to serve and promote the interests of engineering and science firms practicing in multi-media environment management and remediation. Qualified reviewers were recruited from HWAC's Technical Practices Committee. HWAC is pleased to endorse the monograph as technically sound.

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Soil Science Society of America

The Soil Science Society of America, headquartered in Madison, Wisconsin, is home to more than 5,300 professionals dedicated to the advancement of soil science. Established in 1936, SSSA has members in more than 100 countries. The Society is composed of eleven divisions, covering subjects from the basic sciences of physics and chemistry through soils in relation to crop production, environmental quality, ecosystem sustainability, waste management and recycling, bioremediation, and wise land use.

Members of SSSA have reviewed the monograph and have determined that it is acceptable for publication.

The lead reviewer was:

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Water Environment Federation

The Water Environment Federation is a nonprofit, educational organization composed of member and affiliated associations throughout the world. Since 1928, the Federation has represented water quality specialists including engineers, scientists, government officials, industrial and municipal treatment plant operators, chemists, students, academic and equipment manufacturers, and distributors.

Qualified reviewers were recruited from the Federation's Hazardous Wastes Committee and from the general membership. It has been determined that the document is technically sound and publication is endorsed.

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INTRODUCTION

This monograph, covering the *design, applications, and implementation* of vapor extraction, bioventing, and air sparging, is one of a series of seven on innovative site and waste remediation technologies. The series was preceded by eight volumes published in 1994 and 1995 to provide the descriptions, discuss evaluations, and delineate limitations of the several remediation technologies, including vapor extraction. This book complements the first book on vapor extraction by adding specific details on design, construction, and operation of such systems. In addition, this book addresses enhancements to the vapor extraction technology, including dual-phase vapor extraction, bioventing, and air sparging.

This series of design and application monographs is being published as part of the WASTECH® Project, a multiorganization effort involving more than 100 experts. The series provides the experienced, practicing professional with guidance on innovative processes considered ready for full-scale application. Other monographs in this design and application series and the companion series address bioremediation; chemical treatment; liquid extraction; soil washing, soil flushing, and solvent/chemical extraction; stabilization/solidification; thermal desorption; and thermal destruction.

1.1 Vapor Extraction and Air Sparging

1.1.1 Vapor Extraction

Vapor extraction, also known as *soil vapor extraction*, *soil venting*, and *in situ venting*, involves the removal of contaminant-laden vapors from unsaturated soil. A vacuum is applied by a pump or blower through a number of extraction vent wells, vertical or horizontal, inducing gas flow through the soil toward the vents. Certain chemicals volatilize into the clean air drawn from the ground surface, passive vents, or air injection wells. The removed vapors may require treatment before the air is discharged to the atmosphere. The typical components of a vapor extraction system, such as shown in Figure 2.1, include vent wells, manifold piping, control valves to adjust flow, vacuum blowers and controls, pressure gauges and flow meters, an air/water separator, and a vapor treatment unit (Johnson et al. 1994). One of the major advantages of vapor extraction is that most of the components are relatively inexpensive and readily available.

1.1.2 Air Sparging

The removal of volatile chemicals from the subsurface can be enhanced by a number of ways including air sparging, air heating, and other air pretreatments. *Air sparging* involves the injection of air beneath the groundwater table. Air channels form as the air rises to the surface, and volatile chemicals are removed from the contaminated groundwater. In addition, the introduction of air into the subsurface in processes, such as *bioventing* and *biosparging* greatly increases the oxygen concentration, thereby enhancing biological degradation.

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 (NACEPT), convened a workshop for representatives of consulting engineering firms, professional societies, research organizations, and state agencies involved in 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, multi-disciplinary 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, providing for the Academy to manage a project 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 multi-organization 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, the Soil Science Society of America, and the Water Environment Federation, together with the Academy, US 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 initial monographs began in earnest in January, 1992, and the original eight monographs were published during the period of November, 1993, through April, 1995. In Spring of 1995, based upon the reception by the industry and others to the original monographs, it was determined that a companion set, emphasizing design and application of the technologies, should be prepared as well. Task Groups were identified during the latter months of 1995 and work commenced on this second series.

1.2.2 Process

For each of the series, the Steering Committee selected the technologies, or technological areas, to be covered by each monograph, the monographs' general scope, and the process for their development. The Steering Committee then appointed a task group composed of 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, academia, and government.

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 US 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 members of the Committee supplemented by 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.

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 vapor extraction and air sparging site remediation technologies, that is, 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 vapor extraction, bioventing, and air sparging practice.

1.4 Objectives

The monograph's principal objective is to furnish guidance for experienced, practicing professionals and users' project managers. This monograph, and its companion monograph (Johnson et al. 1994), are 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 are potentially applicable.

1.5 Scope

The monograph addresses innovative vapor extraction, air sparging, and bioventing technologies that have been sufficiently developed so that they can be used in full-scale applications. It addresses all aspects of the technologies for which sufficient data were available to the task group to review the technologies and discuss their design and applications. Actual case studies were reviewed and included, as appropriate.

The monograph's primary focus is site remediation. To the extent the information provided can also be applied elsewhere, it will provide the profession and users this additional benefit.

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 that they are essential to understand the applications and limitations of the technologies described:

- site investigations and assessments;
- planning, management, and procurement;
- regulatory requirements; and
- community acceptance of the technology.

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, post-publication 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 is organized under a uniform outline and addresses the design and application of two primary innovative treatment technologies — vapor extraction and air sparging.

Chapter 2, Application Concepts summarizes the scientific principles and potential applications of vapor extraction and air sparging. Design Development for Vapor Extraction, Chapter 3, provides essential information for those contemplating use of vapor extraction and Chapter 4 discusses its implementation and operation. Chapter 5 discusses the development of design and its application for air sparging. The implementation and operation of air sparging systems is discussed in Chapter 6. A series of Case Histories are provided in Chapter 7 for each technology. The Appendices provides details regarding applicable models, safety practices, relevant properties of organic pollutants, and references.

2

APPLICATION CONCEPTS

Vapor extraction, also known as *soil vapor extraction*, *soil venting*, and *in situ venting*, involves the removal of contaminant-laden vapors from unsaturated soil. A vacuum is applied by a pump or blower through a number of extraction vent wells, vertical or horizontal, inducing gas flow through the soil toward the vents. Certain chemicals volatilize into the clean air drawn from the ground surface, passive vents, or air injection wells. The removed vapors may require treatment before the air is discharged to the atmosphere. The typical components of a vapor extraction system, such as shown in Figure 2.1, include vent wells, manifold piping, control valves to adjust flow, vacuum blowers and controls, pressure gauges and flow meters, an air/water separator, and a vapor treatment unit (Johnson et al. 1994). One of the major advantages of vapor extraction is that most of the components are relatively inexpensive and readily available.

The removal of volatile chemicals from the subsurface can be enhanced by a number of ways including air sparging, air heating, and other air pretreatments. *Air sparging* involves the injection of air beneath the groundwater table. Air channels form as the air rises to the surface, and volatile chemicals are removed from the contaminated groundwater. In addition, the introduction of air into the subsurface in processes, such as *bioventing* and *biosparging* greatly increases the oxygen concentration, thereby enhancing biological degradation.

In *bioventing*, the air flow rate is usually reduced to decrease the fraction of chemical removed by volatization and increase the amount biodegraded, thereby reducing the volume of air requiring posttreatment. The same can be said for *biosparging*.

Figure 2.2 illustrates a simplified air sparging/vapor extraction system. In this system, an additional blower/compressor is added to inject air under pressure below the groundwater table. Continuous air channels are formed as the air rises to the surface (Ji et al. 1993; Johnson et al. 1993). The channels branch to form more channels as the pressure decreases and the air volume increases. The upward movement of air in the vicinity of the injection well induces some water movement that brings the contaminated groundwater in closer contact with the air channels, thereby increasing the rate at which the contaminants are removed from the water.

Figure 2.1
Vapor Extraction System

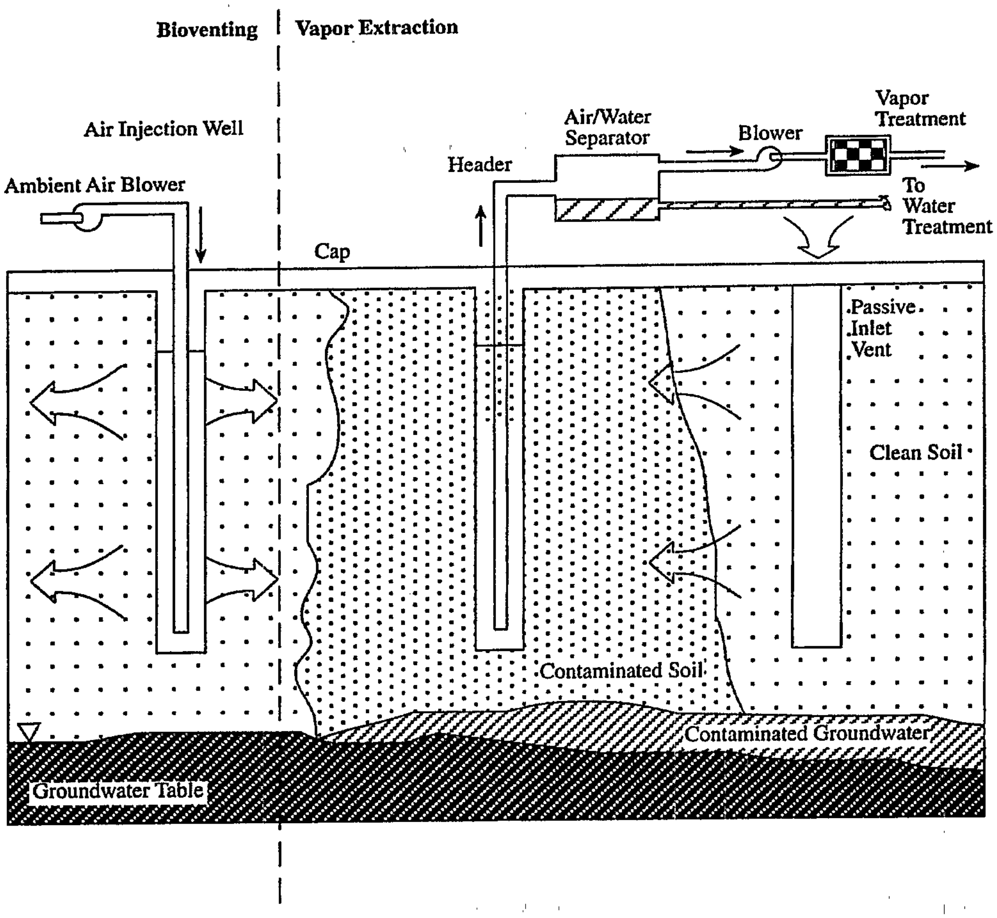
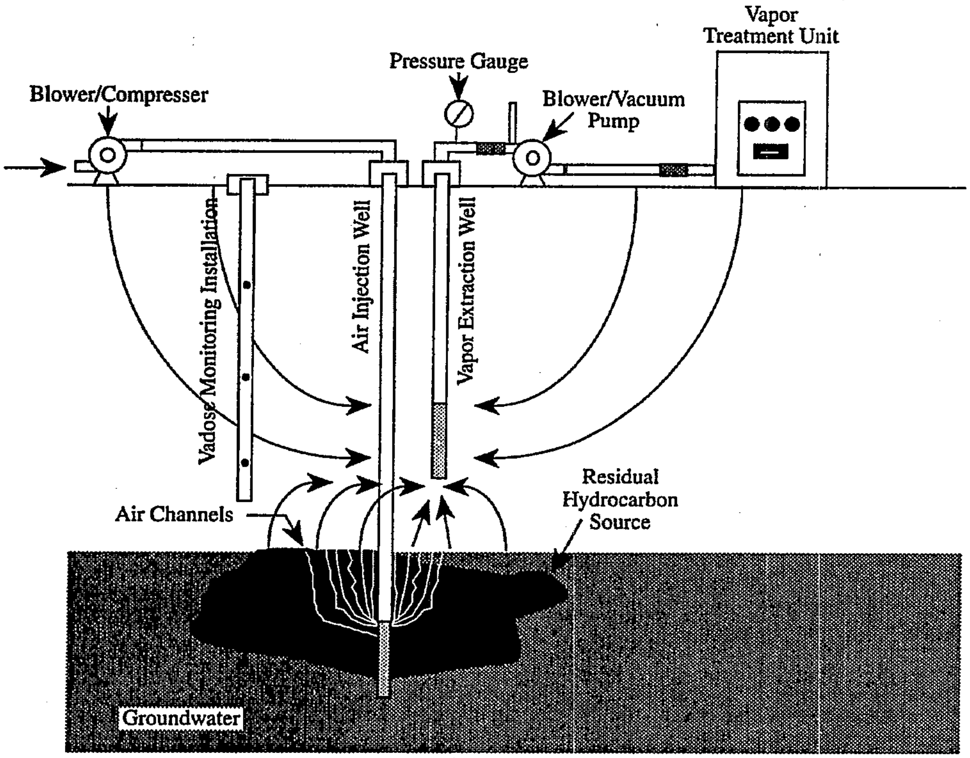


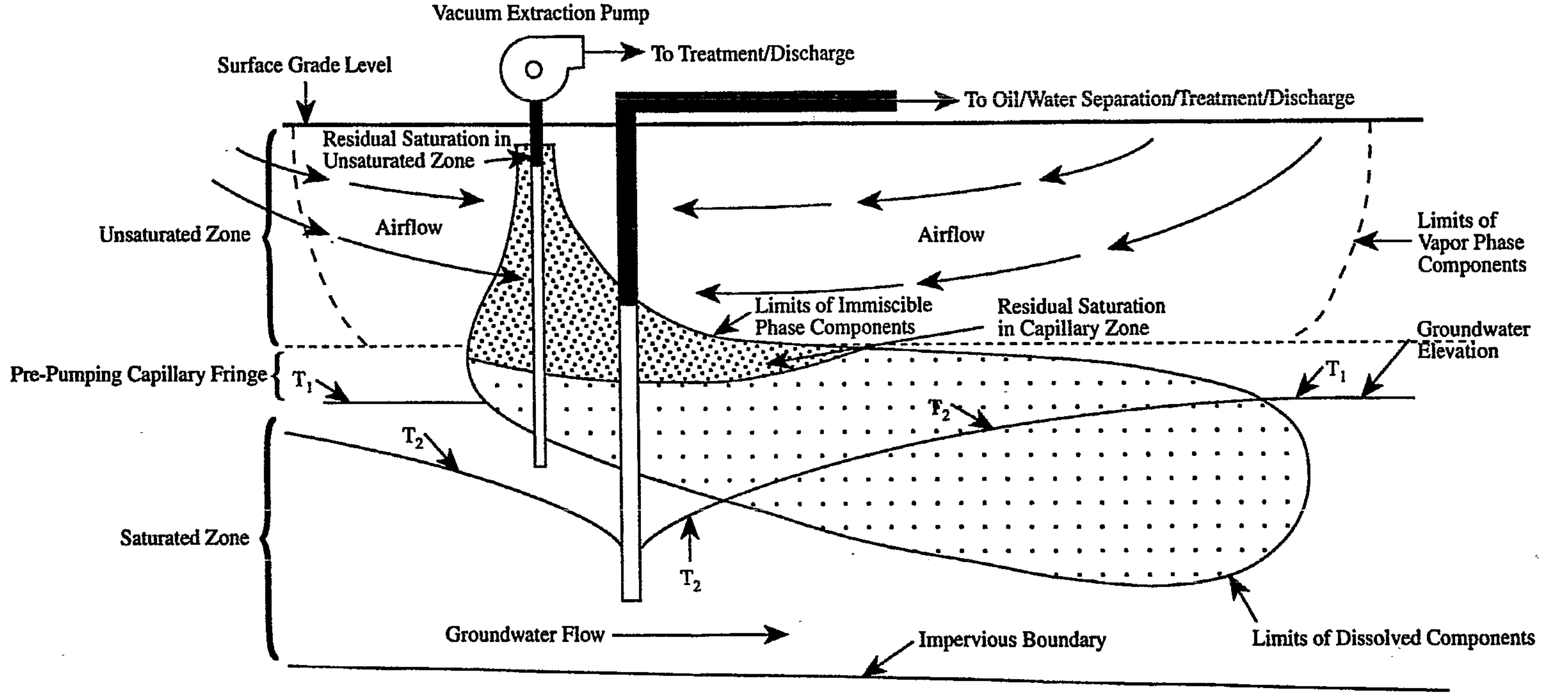
Figure 2.2
Simplified Air Sparging/Vapor Extraction Schematic



Source: Johnson et al. 1994

A variation of air sparging/vapor extraction, *dual-phase extraction*, involves the dual extraction of air and water in an attempt to enlarge the unsaturated zone, thus exposing more soil to the vapor extraction process. Extraction of vapors and groundwater at the same time can be used as a means of controlling groundwater mounding, dewatering soil to enhance vapor extraction or bioventing, and removing nonaqueous-phase liquids (NAPLs), if present. To accomplish this, a separate groundwater pumping well can be installed in the vicinity of the vapor extraction vent as shown in Figure 2.3. In another variation, the liquids pump can be installed in the same casing used for vapor extraction.

Figure 2.3
Dual-Phase Extraction Schematic

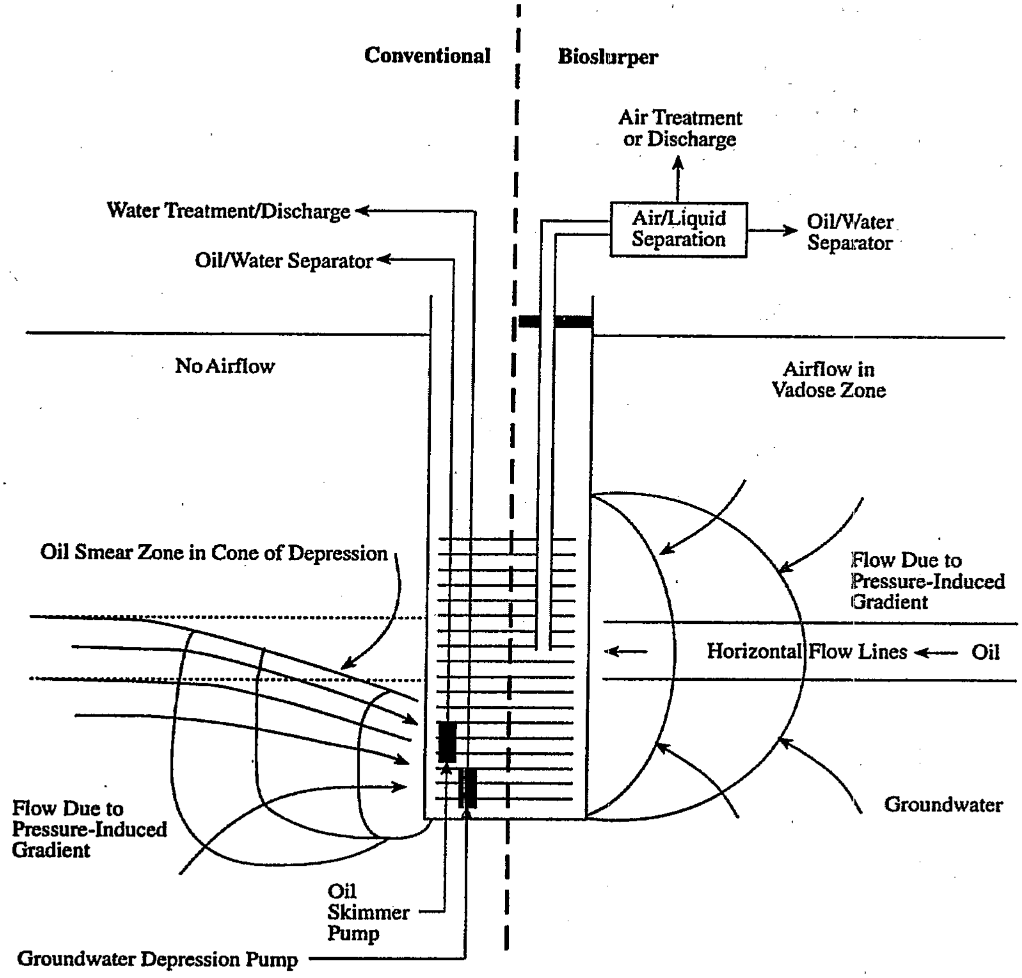


T_1 and T_2 depict pre- and post-pumping positions of water table

Source: US ACE 1995

Figure 2.4 contrasts a conventional light nonaqueous-phase liquid (LNAPL) recovery using a two-pump system with a bioslurper system. In the conventional system, one pump produces a cone of groundwater depression while the other removes the LNAPL that flows toward the well. The

Figure 2.4
Comparison of LNAPL Remediation Using Conventional Two-Pump System (Left) and Bioslurper System (Right)



Source: US ACE 1995

bioslurping system uses a suction tube placed at the NAPL/water interface, producing a pressure (vacuum) gradient causing water, LNAPL, and air to move to the tube without causing a cone of depression and a resulting NAPL smear zone. When slurping is conducted to enhance both free product recovery and biological degradation, the process is called *bioslurping* (Kittel et al. 1994).

2.1 Scientific Principles

The rate of pollutant removal is affected by a number of mechanisms including air flow rates and patterns, mass transport mechanisms, and chemical and biological degradation (Unger, Sudicky, and Forsyth 1995; Clayton et al. 1996). In addition, partitioning dictates the state of chemicals during the vapor extraction/air sparging process.

2.1.1 Chemical Equilibrium

The extent of partitioning of chemicals among the gas, liquid, solid, and NAPL plays a significant role in performance of vapor extraction/air sparging systems. One of the goals of evaluating system performance is to predict the vapor concentrations of volatile compounds in the subsurface. The following discussion assumes a homogeneous, isotropic aquifer matrix. In general, the total volumetric concentration T_j (g-j/cm^3-soil) of component j is distributed in the subsurface among gas, water, soil, and NAPL as described by the mass balance:

$$T_j = \theta_a C_{aj} + \theta_w C_{wj} + \rho_b S_j + \theta_n C_{nj} \qquad (2.1)$$

where: θ_a = air-filled porosity (cm^3/cm^3-soil);
θ_w = volumetric fraction of water (cm^3/cm^3-soil);
θ_n = volumetric content of NAPL (cm^3/cm^3-soil); and
ρ_b = bulk density of the soil (g/cm^3 of soil).

The mass concentrations of j in air, water, and NAPL are C_{aj} (g/cm^3), C_{wj}, and C_{nj}, respectively, and S_j is the mass of j sorbed to the soil solids (g/g-soil)(Johnson et al. 1994).

Raoult's Law is assumed to describe the relationship between the equilibrium concentrations in air and NAPL as follows:

$$C_{aj} = X_j C_{aj}^{sat} \tag{2.2}$$

where: X_j = the mole fraction of j in the NAPL; and
C^{sat}_{aj} = the saturated vapor concentration of j (g of j/cm³-vapor) and is defined as:

$$C_{aj}^{sat} = MW_j P_{vj} / (RT) \tag{2.3}$$

where: MW_j = the molecular weight of j (g of j/mole);
P_{vj} = the vapor pressure of j at temperature T (atm);
R = the gas constant (82 cm³-atm/mole-(K); and
T = the absolute temperature (K).

The partitioning of j between NAPL and water can be described in a manner similar to Equation 2.2:

$$C_{wj} = X_j C_{wj}^{sat} \tag{2.4}$$

where: C^{sat}_{wj} = the solubility of j in water (g of j/cm³-water).

The equilibrium between a chemical in the air and water phases is defined by Henry's Law:

$$C_{aj} = H_j C_{wj} \tag{2.5}$$

where: H_j = the Henry's Law partition coefficient for j.

To maintain consistency with Equations 2.2, 2.3, and 2.5, H_j is defined as:

$$H_j = C_{aj}^{sat} / C_{wj}^{sat} \tag{2.6}$$

Equation 2.5 applies to areas of the unsaturated zone where NAPL is not present.

The partitioning of chemicals to soil solids is described by sorption isotherms where the sorbed concentration is a function of the water-phase concentration:

$$S = f(C_{wj}) \tag{2.7}$$

There are a number of relationships (Langmuir, Freundlich, and BET) that provide a mathematical relationship between the mass sorbed and the aqueous concentration. However, the most commonly used relationship for soil is the partitioning equation:

$$S = K_d C_{wj} \tag{2.8}$$

where: K_d = the partition or distribution coefficient.

By observation, Equation 2.8 is similar to Equation 2.5. Because sorption is often considered to be partitioning of chemicals into the organic fraction of soil, K_d is normalized by the fraction of organic carbon in the soil as follows:

$$K_{oc} = K_d / f_{oc} \tag{2.9}$$

where: K_{oc} = the partition coefficient into organic carbon and f_{oc} is the fraction of soil that is organic carbon.

The utility of K_{oc} is that there are several correlations that relate K_{oc} to chemical properties, such as the octanol/water partition coefficient, K_{ow}, or the water solubility, C^{sat}_{wj}:

$$\log K_{oc} = a \log K_{ow} + b \quad \text{or} \quad \log K_{oc} = c \log C^{sat}_{wj} + d \tag{2.10}$$

where: a, b, c, and d are empirical constants.

Fetter (1993) and Spitz and Moreno (1996) summarize the most commonly used correlations for K_{oc}. The limitations of these correlations are that they are generally developed for a specific class of chemicals and they give a wide variation in the value for K_{oc}, often as high as an order of magnitude. On the other hand, due to the general decrease in soil organic matter with increasing depth, the relative importance of sorption decreases deeper in the soil profile.

2.1.2 Air Flow Principles

Successful operation of in situ aeration systems requires that air flow be established throughout the zone of contamination. The goal is to contact as much of the zone of contamination as possible with air flow because such systems rely primarily on volatilization and subsequent advection of chemicals from the soil and not on the slower process of diffusion to transfer chemicals to the air stream. The air sparging enhancement requires injection of air below the water table and establishment of air flow in the saturated zone. Again, the injection points should be placed close enough to one another to maximize contact between the contamination and the moving air.

2.1.2.1 Air Flow in the Unsaturated Zone

Equations describing air flow in unsaturated soil begin with a mathematical expression of mass conservation:

$$\partial(\rho_a\theta_a)/\partial t+\underline{\nabla}\bullet(\rho_a\underline{q_a})=0 \qquad (2.11)$$

where: ρ_a = the density of the vapor phase (g/cm^3); and
q_a = the specific discharge of the air (darcy velocity).

The first term in Equation 2.11 accounts for the accumulation of air in a given volume of soil; the second term describes the mass flow rate of air through it. The q_a vector is related to the fluid potential Φ (cm^2/s^2) through the following form of Darcy's Law:

$$\underline{q_a}=-(\rho_a/\mu)k_a\bullet\underline{\nabla}\Phi \qquad (2.12)$$

where: μ = the vapor-phase viscosity (g/cm-s); and
k_a = air permeability (cm^2).

For gases, Φ is given by:

$$\Phi=gz+\int_{P_o}^{P}\frac{dP}{\rho_a} \qquad (2.13)$$

where: z = the elevation (cm);
g = the acceleration of gravity (981 cm/s^2);
P = the gas-phase pressure (g/cm-s^2); and
P_o = a reference gas-phase pressure (g/cm-s^2).

The relationship between the vapor-phase density and pressure is given by the ideal gas law:

$$\rho_a=MW_aP/(RT) \qquad (2.14)$$

where: MW_a = the average molecular weight of the vapor phase.

By assuming that gz is negligible and that MW_a is constant, Darcy's Law simplifies to:

$$\underline{q_a} = -(k_a / \mu) \bullet \underline{\nabla} P \tag{2.15}$$

This relationship demonstrates that air flow is clearly a function of pressure gradient. The governing equation can be simplified to:

$$(2\theta_a \mu)\partial P / \partial t = \underline{\nabla} \bullet \underline{\underline{k}} \bullet \underline{\nabla} P^2 \tag{2.16}$$

Appendix A presents a number of analytical solutions for linear and radial flow for one- and two-dimensional scenarios. These are useful for preliminary calculations to estimate air flow as a function of soil permeability, applied vacuums, and radii of flow. Most problems, however, are three dimensional. In this case, it is necessary to use numerical solutions for the governing flow Equation 2.16. Massmann (1989) determined that for extraction vacuums less than about 0.2 atmospheres, air flow behaves as an incompressible fluid and that conventional water flow models such as MODFLOW can be used to simulate air flow. Hauge (1991) was able to simulate field pressure and flow measurements by using a finite-element code developed for groundwater flow by (1) using gas conductivity for hydraulic conductivity, (2) specifying the ground surface and a vertical boundary at an estimated radius of influence, and (3) converting the output pressures interpreted as head in units of air to conventional units of pressure. More recently, a number of numerical models specifically developed for soil vapor extraction have become available. Section 3.2.3 describes several such models.

2.1.2.2 Air Flow in the Saturated Zone

When air is injected below the groundwater table during air sparging, the injection pressure must be high enough to overcome the hydraulic head, the soil air entry pressure, and the piping system pressure losses. In general, the system pressure losses and the air entry pressure are negligible compared the pressure required to overcome the hydraulic head above the injection point. The minimum pressure required from the blower is given by:

$$P_{bl} = 9800\,h \tag{2.17}$$

where: P_{bl} = the blower pressure (N/m^2); and
h = the depth in meters from the top of the injection well screen to the groundwater table.

Air bubbles in most soils collapse on one another to form air channels. The air channel diameters are of the scale of several grain sizes (Johnson et al. 1993). As the air rises, the pressure decreases causing the air volume to increase, and additional air channels form (Ji et al. 1993). Figure 2.5 shows the branching of the air channels in a two-dimensional reactor and the effect of soil layering on the zone of air influence.

Hein et al. (1997) used a numerical model to simulate air fluxes and water saturation in the vicinity of air injection wells. Figure 2.6 depicts the air saturation around a typical air injection well. The figure shows that the zone of air flow is parabolic in shape, similar to that shown in Figure 2.5.

The mass flow rate of air leaving an injection well is constant for a given blower, manifold, and valve arrangement and is given by:

$$G = \rho_a A_{ac} v \tag{2.18}$$

where: G = the mass flow rate of air (g/s);
ρ_a = the density of air (g/cm^3);
A_{ac} = the total area of the air channels (cm^2); and
v = the air velocity (cm/s).

Assuming that the velocity in the air channels is constant, Equation 2.18 can be rearranged to give air channel area as a function of air density:

$$A_{ac} = G / (\rho_a v) \tag{2.19}$$

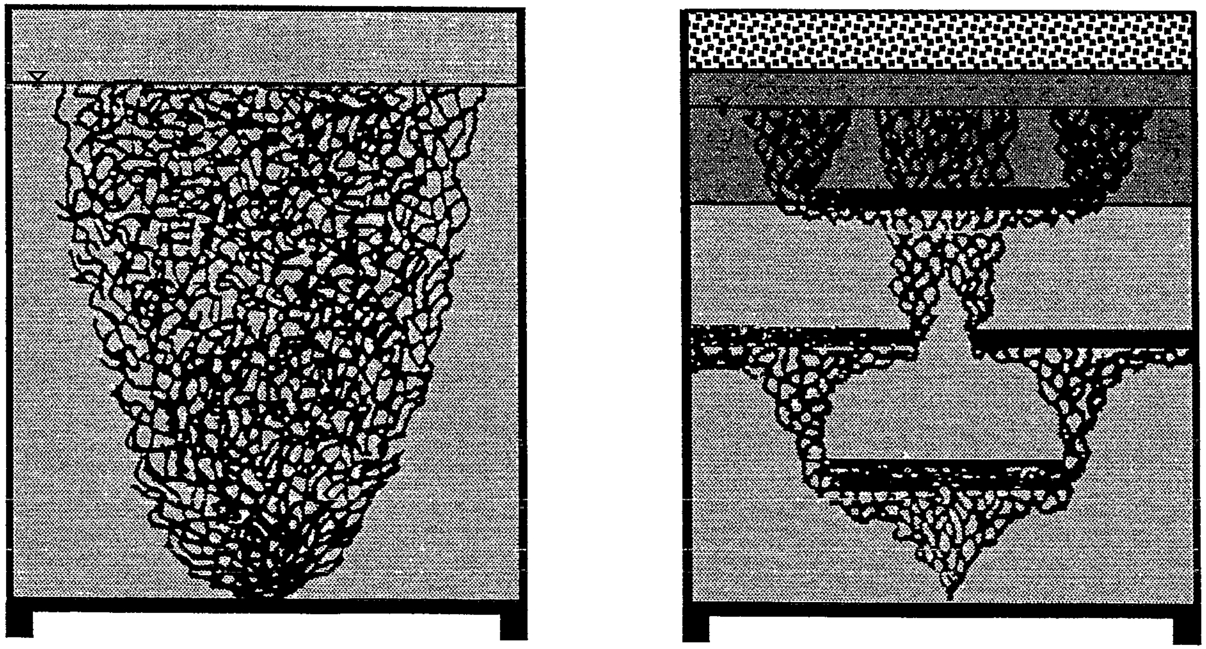
Since ρ_a decreases with decreasing pressure (Equation 2.14), the total air channel area must increase, which, in turn, means that the total number of air channels must increase as the air approaches the groundwater table as is shown in Figure 2.5.

As air rises, it induces water flow currents within the saturated zone, especially in course-grained soils. This has the effect of minimizing the distance that chemicals have to diffuse to move from the water to the air, thereby decreasing the time to remove volatile chemicals from the water.

2.1.3 Mass Transfer Principles

Important mass transfer mechanisms for air sparging/vapor extraction are advection with the air flow, dispersion/gas diffusion within the gas flow, volatilization (which is generally fast relative to other mechanisms), and

Figure 2.5
Two-Dimensional Analysis of Air Sparging

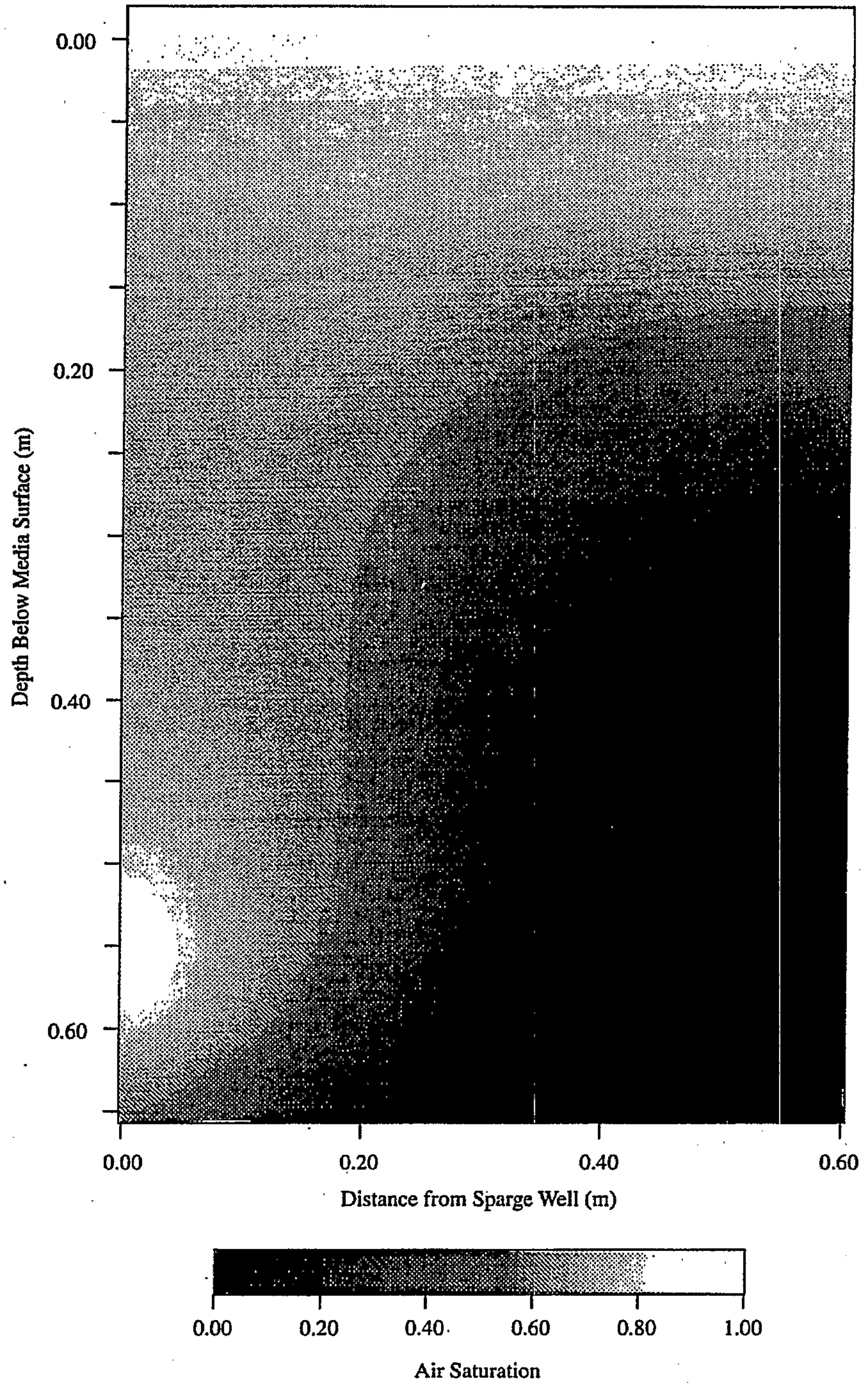


(a) Homogeneous Conditions

(b) Heterogeneous Conditions

Ji, W., A. Dahmani, D. Ahlfeld, J. Lin, and E. Hill (1993). "Laboratory study of air sparging: air flow visualization," *Groundwater Monitoring Review and Remediation*, Fall: 115-126.
Reprinted by permission of Ground Water Publishing Company ©1993.

Figure 2.6
Prediction of Air Saturation in a Cylindrical Laboratory Reactor



Source: Hein 1996

liquid diffusion out of the water. The mass flux due to molecular diffusion is given by Fick's first law of diffusion:

$$F = -D_m dC / dx \tag{2.20}$$

where: F = the mass flux (g/cm^2-s);
D_m = the molecular diffusion coefficient (cm^2/s); and
dC/dx = the chemical concentration gradient.

If diffusion is one-dimensional, then Fick's second law of diffusion, which is a mass balance, becomes:

$$\partial C / \partial t = D_m \partial^2 C / \partial x^2 \tag{2.21}$$

Crank (1975) has compiled solutions to Equation 2.21 for numerous boundary and initial conditions. For example, assuming that a chemical diffuses into or out of a single layer of soil of infinite thickness, the concentration at a given point and time is given by:

$$C(x,t) = C_o \mathrm{erfc}(x / (2(D_m t)^{1/2})) \tag{2.22}$$

where: C_o = the initial concentration at the layer boundary; and
erfc = the complimentary error function.

The implication of Equation 2.22 is that diffusion through water, even a few centimeters, is a relatively slow process. Thus, the removal of chemicals from the subsurface is often diffusion-limited.

The general chemical transport equation for volatile organic chemicals in a mobile fluid is given by:

$$\partial C / \partial t + (1-n)(\rho_s / n)\partial S / \partial t = -\Delta(vC) + D\Delta^2 C - \lambda C - \Sigma Qc_{in} \tag{2.23}$$

where: n = the soil porosity;
ρ_s = the density of soil solid (g/cm^3);
λ = a decay constant (1/s); and
ΣQc_{in} = the sum of other source/sink terms such as the transfer from one phase to another (Spitz and Moreno 1996).

The terms on the left side of Equation 2.23 represent the change over time in mass of the chemical that is in the mobile fluid (water or air) and that is sorbed on soil. The terms on the right side of Equation 2.23 represent the rates of mass: (1) transferred by fluid flow, (2) transferred by diffusion and dispersion, (3) loss to decay, and (4) in or out of the fluid to other sources or sinks. Equation 2.23 can be applied to either water or air flow and generally forms the basis for the development of numerical models for chemical transport in general, and, more specifically, for vapor extraction/air sparging.

2.1.4 Chemical Destruction Principles

While abiotic processes, such as hydrolysis, dehalogenation, and chemical oxidation may be responsible for the decay of volatile organic chemicals, biological degradation is the primary mechanism for the in situ destruction of organic chemicals during vapor extraction/air sparging. The oxygen requirement can be approximated by stoichiometry. For example, complete, aerobic, aliphatic hydrocarbon destruction is given by the following equation:

$$2C_nH_{2n+2} + (3n+1)O_2 \rightarrow 2nCO_2 + (2n+2)H_2O \qquad (2.24)$$

From this, the oxygen requirement is (24n + 8)/(7n + 1) g-O_2/g-hydrocarbon. For octane (n = 8), the O_2 required is 3.5 g/g-octane.

For aromatic hydrocarbons such as benzene, aerobic destruction is given by:

$$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O \qquad (2.25)$$

The oxygen requirement is 3.1 g-O_2/g-benzene. Since the mass fraction of oxygen in air is 0.231 g-O_2/g-air, there should be no trouble providing enough oxygen to degrade hydrocarbons if air is supplied to the subsurface.

Biodegradation kinetics can be expressed mathematically as a hyperbolic function, as given by the Michaelis-Menten equation:

$$R = -VC/(K+C) \qquad (2.26)$$

where: R = the reaction rate (1/s);
V = the maximum biodegradation rate (1/s); and
K = the half-saturation constant (mol/L).

The half-saturation constant is the contaminant concentration at which the biodegradation rate is half that of the maximum biodegradation value (US ACE 1995). C is the concentration of the chemical that limits the rate of biodegradation. While this chemical is usually assumed to be the contaminant of interest, it also could be nitrogen or phosphorus. Although atypical, nitrogen and/or phosphorus may need to be injected to achieve maximum degradation rates.

From Equation 2.26, it can be seen that at high concentrations ($C >> K$), the reaction rate is independent of concentration:

$$R = -V \tag{2.27}$$

At low concentrations ($C << K$), the reaction rate approaches a first-order rate:

$$R = -FV \tag{2.28}$$

where the first-order rate constant F is approximated by V/K.

2.2 Potential Applications

Application of vapor extraction, air sparging, and associated variations should be considered as a part of an overall site remediation strategy. For example, it may be cost-effective to contain a contaminant plume using flow barriers or pumping strategies. If free product exists as LNAPL, a free product recovery system may be installed and operated before implementing vapor extraction. Groundwater pumping may be used to lower the water table, thereby increasing the volume of unsaturated soil to be treated by vapor extraction. If emission rates are low, there are no receptors in the area, and biological activity is the primary destruction mechanism or if there is significant biodegradation in the vadose zone, vapor extraction may not be needed as part of an air sparging system.

2.2.1 Vapor Extraction

Vapor extraction is now a well-established technology for the removal of volatile organic chemicals from unsaturated soil (Hutzler, Murphy, and Gierke 1990; Johnson et al. 1994). (Semivolatile compounds may be treated by bioventing.) The technique works well in sandy soils with high permeabilities, for chemicals with vapor pressures greater than 5 mm Hg, and where site conditions are well defined. Conversely, vapor extraction is usually not recommended for massive clays unless mechanical mixing is used (Siegrist, West, and Gierke 1995). Sites with complicated geology and underground structures and where the location of contamination is uncertain require much more characterization and pilot testing. Figure 2.7 is a flowchart for evaluating the suitability of vapor extraction and bioventing. Most of the steps listed in Figure 2.7 are discussed in this monograph.

2.2.2 Air Sparging

Air sparging is a newer technology. However, a growing body of literature indicates a broad applicability of the technique. Table 2.1 cites a number of cases where air sparging has been used to successfully remediate groundwater. Soil types range from silty sand to sands and gravels. Cleanup is usually completed within 24 months.

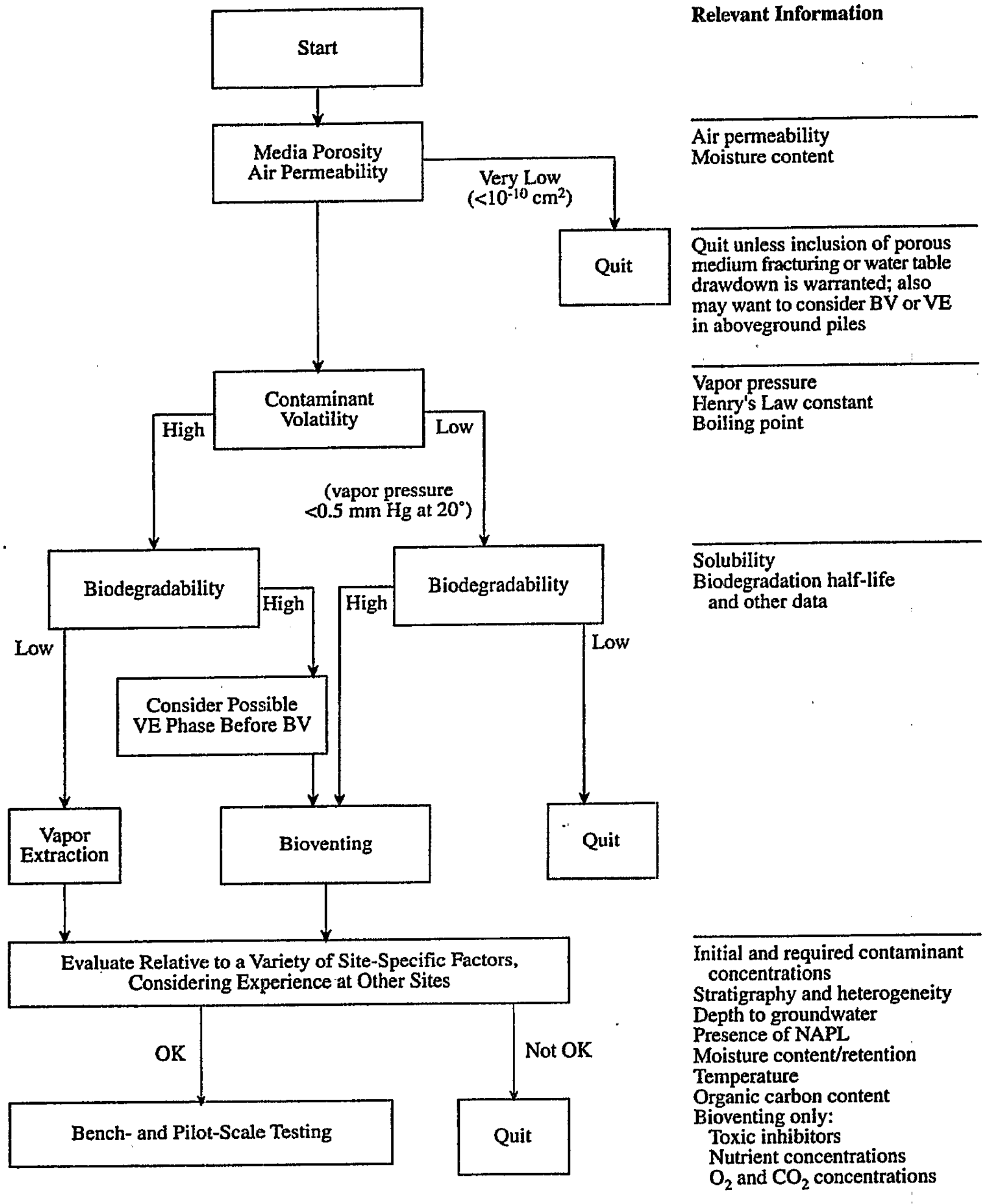
Most of the tests summarized in Table 2.1 were completed in relatively shallow aquifers with a maximum injection depth of 30 ft. The range of injection pressure for sparging ranged from approximately 2 to 60 psi, and the flow rates ranged from 1 to 50 scfm. None of these tests exceeded 2 years. These site applications indicate that air sparging can accomplish groundwater cleanup much more quickly than conventional pump-and-treat operations. Because there is little site disturbance, the equipment can be easily removed, and the site can be returned to its original appearance (Hein 1996). Sparging has been most successful with light hydrocarbons and chlorinated solvents.

2.2.2 Range of Applicability of Vapor Extraction/Air Sparging Technology

Vapor extraction, bioventing, and air sparging, along with their modifications, have been applied to a wide range of sites. At any given site, a number of physical, chemical, and biological conditions, such as geologic structure and soil properties (particle-size distribution, porosity, and moisture content), chemical properties, and biodegradability, have a significant impact on the success of these technologies. Thus, the importance of site characterization cannot be overemphasized.

Soil borings and geophysical techniques provide information on the nature of soil horizons, moisture content, and texture. Subsurface features, such as sandy or gravelly layers, promote preferential flow paths, while finer-textured soils containing contamination indicate a system where contaminant removal will be limited by chemical diffusion. In industrial and

Figure 2.7
Technology Screening Decision Tree for Vapor Extraction (VE) and Bioventing (BV)



Source: US ACE 1995

urban locations, the contrast between native soil and disturbed soil or fill should be discerned. Vapor extraction, bioventing, and air sparging have been applied over a wide range of soil permeabilities; the major difference is the extraction/injection pressures and the time taken to complete remediation. Soils with an intrinsic permeability less than 10^{-10} cm^2 are not likely candidates for vapor extraction/air sparging.

Chemicals most amenable to vapor extraction are volatile (vapor pressure greater than about 5 mm Hg), have low Henry's Law constants, and include gasoline, kerosene, diesel fuel constituents, and solvents, such as tetrachloroethene, trichloroethene, and methylene chloride. Chemicals that tend to be highly biodegradable include compounds with low Henry's Law constants, such as gasoline, jet fuel, toluene, benzene, acetone, ketones, and phenols. Fuel and lubricating oils, creosotes, and long-chain aliphatics are moderately degradable, while chlorinated solvents and pesticides are difficult to degrade (Clayton et al. 1996).

2.2.3 Limitations of Technology

Vapor extraction, bioventing, and air sparging are usually not considered for sites that do not meet the conditions outlined in Section 2.2.2. Nonetheless, research continues to extend the utility of this technology by use of techniques, such as soil fracturing, soil mixing, and soil heating. Additional limitations include the uncertainty in predicting time to cleanup or closure since few predictive tools are presently available. Bench- and pilot-scale testing as outlined in this monograph are still required to optimize design of this technology. Several examples are given throughout this book on the limitations of each approach. A more detailed coverage of the physical, chemical, and biological factors that constrain the performance of these technologies is beyond the scope of this monograph.

Table 2.1
Reported Air Sparging Field/Laboratory Applications

Soil Description, Scale, and Application[a]	Chemical	Injection Pressure (psi)	Reported Radius of Influence (ft)	Air Flow (SCFM)	Duration (days)	Reference
Stratified to very fine sand, well 15 ft below water table	TCE	15-60	6	3-10	30	Marley, Hazebrouck, and Walsh 1992
Fine to medium sands with fine gravel, cobbles, and silt, shallow wells installed 6 ft below water table	Gasoline	17	Unknown	1-3	6 hr (pilot test)	Marley, Hazebrouck, and Walsh 1992
Well-sorted fine to medium sands, 17-19 ft below ground surface, varying water table	Gasoline	4-6	Wells installed 12-15 on center	3-5	600 (intermittent operation)	Marley, Hazebrouck, and Walsh 1992
Sandy fill underlain with alluvial sands and glacial outwash, depth of sparging wells unknown, pilot test	PCE, TCE, Gasoline	4, 5, and 8	35	Unknown	1-2 hr	Leonard and Brown 1992
Fine and medium sand, some silt and gravel, sparge well was minimum of 10 ft below water table	Gasoline	10	> 50	4	20 hr/day for approx. 5 months, pulsed well operation	Felten et al. 1992

Medium-grained sand — 25 ft deep, 3 ft of fine silty sand, 11 sparging wells inst. approx. 28 ft below grade, pulsed oper.	Gasoline, Kerosine	14	35	25	70% decrease after 3 months	Peterson, Alfonsi, and Livasy 1993
Poorly-sorted medium sand, sparge well 2.5 m below water table, laboratory test (30 ft by 35 ft by 15 ft)	Syn. hydr. C_5-C_{10}	Unknown	Approx. 1.5 m	5-7	2	Johnson et al. 1992
Paved region with 25 ft sand layer overlying a clay layer with a minimum of 40 ft of sand below the clay, unconfined water depth: 19 ft, confined water depth: 40 ft, pilot test	Gasoline	2.1, 3.9, 8.6, 6.6, 6.0	17	2.1, 4.0, 8.9, 6.5, 6.1	70 min, 75 min, 15 min, 100 min, 135 min	Brown, Payne, and Perlwitz 1993
Medium sand to a depth of 25 ft, fine silty sand to 28 ft, clay layer at 28 ft, depth to water table is approx. 8 ft	Gasoline	14	35	50	3 months	Peterson, Alfonsi, and Livasy 1993
Hetero. porous media, 9 sparging wells	Acetone, TCE, DCE, DCA, PCE, Petr. Hydro.	2, 3	30	200 (total)	4 months	Barrera 1993
15 ft of clay and silty clay overlying 1-3 ft of more perm. clayey silts and silty fine sands	Gasoline	4.5	15	8	33	Barrera 1993

[a] Unless specifically noted, the scale of application was field-scale.

3

DESIGN DEVELOPMENT FOR VAPOR EXTRACTION

This chapter provides in-depth guidance for developing vapor extraction and bioventing system designs. In general, the design process is comprised of the following three steps:

1. *Formulate Design Objectives, Design Constraints, and Clean-up Concentrations and the Method(s) Used to Measure Them.* These parameters, plus a thorough understanding of site characteristics, enable the engineer to complete a conceptual system design. The importance and role of conceptual designs is discussed in Section 3.1.
2. *Develop a Preliminary Design.* Based on a quantitative evaluation of the planned system that often includes pilot tests and air flow modeling, the engineer develops a preliminary design. All of the main system design parameters, such as well spacing and configuration, flow rates, treatment equipment, and equipment location are established. Most of the major decisions that will determine the overall cost and eventual success of the design are made during the preliminary design. Preliminary design is discussed in Section 3.2.
3. *Complete the Final Design.* For the final design, mechanical, electrical, structural, and instrumentation and control plans and specifications are developed to the extent required for construction. Details on the final design step are presented in Section 3.3.

3.1 Soil Remediation Goals

3.1.1 Selecting Design Objectives

The first step in the design process is to determine the overall design objectives and design constraints for the vapor extraction/bioventing system. The design team needs to determine:

- if the contaminant mass removal mechanism is going to be primarily physical removal (volatilization), biological degradation, or some combination of both. This will determine if the system is primarily a vapor extraction or bioventing system.
- if the vapor extraction/bioventing system is: (1) a soil clean-up system, designed to achieve a targeted soil clean-up goal, or (2) a long-term containment system. Most vapor extraction/bioventing systems are for soil cleanup, but occasionally for sources that cannot be removed (e.g., landfills) or that cannot cost-effectively be removed, vapor extraction/bioventing may be used for long-term vapor-phase contaminant control.
- the rate and duration of soil cleanup. For example, design objectives may include extracting soil vapor so that offgas emissions stay below concentrations requiring active treatment, injecting only enough air into the soil to maintain aerobic conditions, or maximizing the rate and minimizing the duration of vapor extraction/bioventing activities.
- site-specific constraints, such as buildings, roadways, underground structures, and property limits that may affect where wells are installed or influence well selection (i.e., vertical versus horizontal wells).
- who is going to operate the system, the level of sophistication required in the controls, and where the process equipment will be housed.
- the integration of vapor extraction/bioventing equipment with other groundwater clean-up equipment being used on the site.

Once these design objectives and constraints are determined and the target zone is sufficiently delineated, the engineer can complete a conceptual model of the vapor extraction/bioventing system. The conceptual model shows the general placement of wells in relation to the zone or zones of contamination and different soil types within the zone of contamination, an initial screened interval of the wells, the use of vapor extraction and/or air injection wells, the use of horizontal versus vertical wells, and the general layout of the system within above- and belowground site constraints. A proper conceptual understanding of what the system needs to accomplish sets the framework for the more quantitative design evaluation. The engineer, as discussed below, can then employ standard gas flow and contaminant partitioning equations to determine well spacing, flow rates, and mass removal rates based on the site-specific contaminant concentrations and the soil air permeability.

3.1.2 Establishing Soil Clean-up Criteria

Concurrent with establishing overall design objectives is the process of identifying site-specific chemicals of concern and associated soil clean-up criteria. The site-specific soil clean-up criteria are necessary to establish the vertical and horizontal extent of the vapor extraction/bioventing target area. Typically, the primary objective is to affect a percent removal of existing contaminant concentrations that achieves risk-based clean-up criteria. This target area is central to the overall design objectives regarding duration and type of cleanup.

Increasingly, risk-based corrective action methods are being employed to determine the level of site cleanup required. With such methods, the risk posed by a site is determined from the location of potential receptors, the possible exposure pathways, and the contaminant concentrations that may reach the receptor. Exposure pathways can include direct contact with surface or subsurface soil, windblown dust and vapor transport, subsurface soil vapor transport, and dissolved-phase contaminant transport in groundwater. Setting soil clean-up goals is complicated by the fact that geologic features (soil type, relation of soil contamination to groundwater), receptor locations, and chemical concentrations vary from site to site. In addition, the location of points of compliance, exposure assumptions, and acceptable risk vary from state to state. Regulatory programs also vary in relation to the application of risk assessments. For example, for underground storage tank (UST) related cleanups, there is a growing trend among many states to use the specific American Society for Testing and Materials (ASTM) standard for risk-based corrective action (E-1739-95). Federal regulators have not adopted the ASTM standard for programs such as CERCLA and RCRA, but increasingly are considering the use of land restrictions to limit potential receptors and to apply chemical fate and transport models to assess how contaminants may migrate from a site.

The end result is that soil clean-up criteria can vary over several orders of magnitude from site to site — there is no typical or universal soil clean-up criteria. For example, soil clean-up concentrations for benzene in one state range from 24 µg/kg for sites where drinking water sources are being protected to 24 mg/kg for some types of commercial sites. Other petroleum hydrocarbons and chlorinated solvents exhibit ranges from low part per billion concentrations for groundwater protection to the tens of parts per million for direct contact on a commercial site.

While soil clean-up criteria are often established before the actual cleanup is undertaken, at some sites the clean-up criteria are based on what is technically and, to a certain extent, economically feasible (referred to as technology-based clean-up criteria). In such cases, rather than operating a system until some specific concentration is met in the soil or offgas, a reasonably designed system is operated until there is little additional mass removal. Then it is shut down, and the cleanup is considered complete or other technologies/containment strategies are employed.

For additional information in determining site-specific clean-up concentrations, refer to:

- Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites, ASTM E-1739-95;
- Interim-Final Risk Assessment Guidance for Superfund (Part A and Supplemental Guidances) US EPA, December 1989; and
- State-specific clean-up guidance.

3.1.3 Measuring Soil Clean-up Criteria

Early in the design process, engineers need to account for how cleanup will be assessed so that appropriate monitoring techniques can be implemented with the design. This section discusses several methods that have traditionally been used to assess the completeness of soil clean-up.

The easiest and least expensive method for tracking soil clean-up is to monitor the contaminant concentrations in the offgas while the system is operating. Offgas contaminant concentrations typically decline asymptotically, and when offgas concentrations reach a predetermined concentration or rate of decline, the system can be shut off. However, there are several drawbacks to this method. First, vapor-phase contaminant concentrations may be diluted with vapor from clean soils and therefore are not representative of the target zone soil. Second, since most soil vapor flow comes from soil near the vapor extraction wells, the offgas is not representative of all the soil in the target zone. Third, the rate of contaminant desorption from the soil is slow compared to the air flow through the soil. As a result, vapor-phase contaminants are not in equilibrium with, and thus are not representative of, the adsorbed-phase contaminants. Fourth, changes in soil air permeability will result in preferred air flow channels (either on a pore scale or macro scale) and so the offgas contaminant concentrations are indicative of only the more permeable soil zones.

An improvement to this method is to shut down the vapor extraction system for a predetermined time period (days to weeks) and then restart the system. In this case, the vapor-phase concentrations may be in equilibrium with, and therefore more representative of, the soil concentrations, but dilution of soil vapor due to air permeability differences and other air dilution factors will still occur. Still, this method of shutting down and subsequently restarting vapor extraction systems is commonly used to assess system performance.

Another way to assess soil clean-up levels through vapor-phase analysis is to collect vertically and horizontally discrete soil gas samples from the target zone after the vapor extraction system has been shut off. The gas samples are then analyzed for the site contaminants. This method is described in detail in the first edition of the *Innovative Site Remediation Technology: Vacuum Vapor Extraction* (Johnson et al. 1994). This method overcomes some of the dilution and nonequilibrium limitations of the methods previously described. A similar technique can be used for assessing the progress of bioventing systems. However, instead of collecting soil vapor samples for analysis of vapor-phase contaminants, the change in oxygen content over time is assessed through a respiration study. Such studies typically track the oxygen demand of soils resulting from aerobic biodegradation over time. Oxygen uptake rates may range from 1 to 20% per day. When no further oxygen uptake is observed after shutdown of a bioventing system, the biological activity in the soil is no longer oxygen limited and further active bioventing may not be warranted.

Finally, soil cleanup can be assessed via collection and analysis of soil samples — the most costly and time-consuming method. US EPA has provided statistical methods of evaluating soil clean-up standards in its *Methods for Evaluating the Attainment of Cleanup Standards, Volume 1: Soil and Solid Media* (US EPA 1989). Such sampling involves careful planning regarding acceptable levels of uncertainty in the decision process, development of a sampling and analysis plan (random versus systematic sampling, simple versus stratified sampling, sequential sampling), determining field sampling procedures, and finally, statistical analysis. Often, project staff with backgrounds in analytical chemistry and statistics are employed in setting up and executing such sampling plans. The cost for such sampling even at a 1-acre site may be tens of thousands of dollars. The advantage to this method is that soil sampling provides the most rigorous documentation of soil cleanup achieved. A disadvantage of soil sampling is the assumption that the collected samples are representative of the entire site, which may not always be true.

There is no universal method to measure the attainment of soil clean-up criteria. The techniques discussed above should be considered a continuum with the first ones being employed early in a project while the later ones are employed only after more certainty exists that clean-up levels have been achieved. Even then, the extent of soil sampling and the amount of statistical rigor will vary given the size of the site and the sensitivity of future releases. Smaller UST releases may be closed with only a few soil samples, while larger CERCLA and RCRA sites may require significant investment in soil sampling and statistical interpretation.

3.1.4 Achievable Soil Clean-up Concentrations

Despite the thousands of vapor extraction projects completed in North America, there are few published examples where a statistically significant number of soil samples were collected in the treatment zone after remediation to assess the final soil clean-up concentrations. In sites favorable for vapor extraction (uniform and coarse grain material), volatile organic compounds (VOCs) (contaminants with a Henry's constant greater than $5 \cdot 10^{-3}$ atm m^3/mole) can be treated to the part per billion range (and often to the lower part of this range). For example, at one Superfund site with a uniform sandy material, 106 samples were collected to document soil cleanup over a less than 1-acre area. The results are shown in Table 3.1.

Table 3.1
Pre- and Posttreatment Soil Sample Analysis Results for a Superfund Site

VOC	Maximum Detected Pretreatment Soil Concentration (μg/kg)	Maximum Detected Posttreatment Soil Concentration (μg/kg)
Methylene Chloride	4,390	2
Acetone	1,166	180
1,1,1-Trichloroethane	500	4
Trichloroethene	2,470	47
Benzene	17	1
Tetrachloroethene	23,600	54
Xylene	35,000	4
Toluene	19,000	73
Ethylbenzene	7,420	4

Source: US EPA 1995a

Sites with less favorable geology (clay soils, high moisture content, soil heterogeneity) have more varied success in the VOC removals achieved. Part of the variation is due to the intensity of soil treatment. Application of high vacuums in conjunction with soil fracturing and hot air injection will yield more mass removal than with low-to-moderate vacuum vapor extraction. Many sites with unfavorable geologic conditions have still been remediated with vapor extraction. The American Petroleum Institute has reported that when vapor extraction was implemented in tight soils after controlled releases of chlorinated solvents, less than 50% of the solvents were recovered. Thus, there is no general guidance to achievable clean-up levels for either less permeable soil or less volatile contaminants. Final contaminant reduction can be as high as 90%, based on site characteristics and intensity of treatment. Section 3.4 discusses process modifications that can be employed at difficult sites to improve the likelihood of success.

The U.S. Air Force has been studying the fate of benzene, toluene, ethylbenzene, and xylenes (BTEX) and total petroleum hydrocarbons (TPH) at more than 50 bioventing sites. The decreases in TPH concentrations attributable to bioventing vary significantly. Even when very little actual change in TPH is found, BTEX concentrations, which comprise only a portion of the TPH measurement, typically are reduced to less than 1 mg/kg after one year of bioventing.

3.2 Design Basis

The design for vapor extraction systems is usually based on the assumption that air in the vadose zone moves under the influence of vapor extraction in a radially symmetric manner toward the extraction well. Although symmetrical air flow rarely occurs in the subsurface, this assumption establishes a starting point for design. The fundamental design parameter is therefore the *radius of influence* (ROI), which is determined from analysis of pilot test data. The ROI is sometimes defined as the extent of measurable vacuum in the subsurface during vapor extraction. In more sophisticated analyses where subsurface vacuum levels are evaluated in terms of the magnitude of the induced air flow, the ROI can be defined as the distance from the extraction well within which a target remediation can be achieved within a desired time frame. In either case, the presumption is that air flows as a continuous fluid throughout the entire unsaturated zone. Vapor extraction system design should be based on providing adequate air flow to achieve remediation goals over the entire treatment area, while providing sufficient conservatism and flexibility to account for the deviations from perfect symmetry, which are inevitable in actual field conditions.

3.2.1 Site and Contaminant Characteristics

The success of vapor extraction is determined by the extent to which air can be made to flow through contaminated soil and the response of the contaminant (i.e., volatilization and/or biodegradation) to air flow. However, complete characterization of the contaminant distribution and the site parameters that determine air flow is rarely practical or cost-effective. A point of diminishing returns occurs regarding the data needed for design and the cost of data collection. Air flow during vapor extraction is likewise rarely uniform and follows preferential paths. Contaminants in high-permeability paths are removed quickly, but remediation of lower permeability zones is limited by diffusion. Despite these limitations, studies of site and contaminant characteristics can yield some general insights into the applicability and potential effectiveness of vapor extraction, the nature of air flow through the subsurface under vapor extraction conditions, and the initial offgas treatment requirements. For a relatively small investment of time and resources in a brief pilot test (often a half-day test is sufficient), a reasonable basis for vapor extraction system design can be obtained. More elaborate testing may be performed, depending on the scope of the envisioned full-scale system, the regulatory requirements, and the complexity of the site. (Also, pilot tests for high-vacuum and dual-phase extraction of low-permeability soils often must be longer because the air permeability of the soil changes as moisture is removed, and steady-state conditions may not be reached for weeks or months.) The greater the investment in site soil and contaminant characterization, the greater the confidence with which the full-scale vapor extraction system can be designed. However, regardless of level of site characterization, vapor extraction system performance almost always deviates from expectations to some extent, and overdesigns, mid-course corrections, and reassessment of remediation goals are common.

The site and soil parameters that are commonly measured and used as a basis for design include background parameters, which are determined prior to any pilot testing at the site and parameters that are assessed from observations during or changes resulting from pilot testing. Background parameters include:

- *Remedial Objectives.* Clearly the first site parameter that should be defined is the goal of the remediation. For example, designs that employ vapor extraction to protect a building from vapors, to evaporate a separate-phase hydrocarbon on the water table, or to remediate adsorbed-phase contamination in unsaturated zone soils would likely be very different from each other.
- *Areal and Vertical Extent of Contamination.* The better the extent of contamination is defined, the more efficient the vapor extraction system will be at addressing the contamination.

Underestimating the extent will leave some area untreated, while overestimating the extent will result in unnecessary expenditures for equipment, operation, and offgas treatment. A soil gas survey may help delineate the extent of the source zone, especially at sites with relatively shallow groundwater. Samples from soil borings should always be carefully monitored for organic vapors.

- *Soil Gas Analysis.* Soil gas samples collected from water table monitoring wells or vapor monitoring points prior to any remediation activity can also provide information on the extent of contamination. The analysis can be repeated during or after operation of a pilot- or full-scale vapor extraction system to evaluate the extent of impact of vapor extraction.
- *Activity at the Site.* The requirements for remediation system installations at active and abandoned sites can vary substantially. For example, vacuum lines must ordinarily be buried or carried overhead at active sites, but can be placed at grade at abandoned sites. Also, the degree of public access (for example, a retail site compared with an industrial site) can dictate the ease of accessibility of various system components in the vapor extraction design.
- *Accessibility.* Constraints are often placed on vapor extraction system designs by the presence of buildings in active use, storage tanks, utilities and pipe trenches, pump islands, and property boundaries. These constraints can affect the placement of vapor extraction wells and their method of installation (e.g., angle drilled, horizontal, etc.).
- *Nature of Ground Surface.* A tight surface seal created by a concrete slab can dramatically affect air infiltration and hence the design of multiple-well vapor extraction systems. In most cases, asphalt does not create a tight surface seal.
- *Stratigraphy.* Low-permeability lenses increase the likelihood that a significant portion of the remediation will be diffusion-limited. Strata of substantial thickness must be addressed by separate remediation systems. Stratigraphy is identified from soil borings and/or test pits. In addition, column tests on undisturbed samples can be used to estimate how much contaminant can be removed from a small volume of soil before diffusion limitations dominate.

- *Soil Organic Carbon Fraction.* This factor affects contaminant partitioning. High levels of organic carbon, such as those typically found in peat, can significantly compromise the effectiveness of vapor extraction on contaminants that adsorb to organic matter.
- *Depth to Groundwater and Thickness of Contaminated Vadose Zone.* The greater the thickness of the vented interval, the more air flow is required. Seasonal water table variation must be taken into account when selecting the screened interval for the extraction wells to ensure the wells are never fully submerged.
- *Subsurface Vacuum.* While this is one of the key parameters during measured pilot test evaluations, it is essential to evaluate the ambient subsurface vacuum levels as well to ensure that tidally- and/or barometrically-induced fluctuations will not confound pilot test measurements.

The U.S. Army Corps of Engineers (US ACE) describes several additional soil parameters that can be measured through laboratory analysis of soil samples (US ACE 1995). Moisture content (measured in the field via neutron probe or in the laboratory) and the soil moisture retention curve (from an undisturbed soil sample) affect the relative air permeability (k_r). Other soil parameters sometimes measured include grain-size distribution, moisture content, bulk density, and porosity. These parameters can enhance understanding of more complicated sites. However, the air permeability (k_a), is typically evaluated and used as a basis for design.

When use of bioremediation is anticipated, soil nutrients (nitrogen and phosphorous concentration and speciation and pH) are measured to ascertain whether nutrient addition will be required. In addition, the soil bacteria populations can be assessed in the laboratory to evaluate the viability of bioventing, although this is commonly done through an in situ respirometry test performed during pilot testing.

Parameters evaluated during pilot testing include:

- *Air Permeability (k_a).* The single most important soil parameter is the flow achieved in response to an applied vacuum. It determines how much air can be delivered to the subsurface to effect remediation. Air flow response is typically measured directly in a field test and the air permeability is derived from this measurement.

- *Horizontal-to-Vertical Permeability Ratio (k_H/k_v).* This parameter determines the distribution of air through the subsurface and the infiltration of air from the ground surface. The ratio is based on vacuum dissipation with depth and distance from the vapor extraction well and the vadose zone thickness.
- *Surface Permeability (k_s).* Vapor extraction is often conducted under an engineered surface seal, pavement, building, or naturally-occurring low-permeability layer, any of which could have a profound impact on surface air infiltration. Surface seals have the greatest effect when vapor extraction is applied to shallow, porous soils (<5 ft). However, surface seals are not always as tight as anticipated. Cracks in, and gravel bases for, pavement and building foundations and vertical fractures in clays often allow significant air infiltration. The effectiveness of a surface seal can be assessed using the vacuum dissipation with distance from the vapor extraction well and the vented interval thickness.
- *Vapor Extraction Offgas Composition.* The change in concentration of volatile contaminant vapors in the vapor extraction offgas over the course of a pilot test lends insight into the location of the vapor extraction well relative to the contaminant source and the offgas technology required to treat the vapors. In extended pilot tests, the rate of change in VOC concentrations can reflect on the potential for mass removal before contaminant removal becomes diffusion-controlled. Measurements of oxygen and carbon dioxide in vapor extraction offgas also reflect the extent of bioremediation in the subsurface. Offgas analyses are typically performed on-site with hand-held field screening instruments; it is important to confirm these readings periodically with off-site laboratory (TO-12/TO-14 or US EPA Method 18) analyses.
- *In Situ Respirometry.* To evaluate the viability of bioventing, an in situ respirometry test is commonly performed in which biological activity is determined from the change in oxygen and carbon dioxide immediately following termination of vapor extraction.

In addition to site and soil parameters, there are certain contaminant properties that affect ventability, including volatility, aqueous solubility, and biodegradability (see Section 2.2). The first two of these determine the contaminant partitioning and hence the thermodynamic driving force for the contaminant to enter the vapor-phase where vapor extraction can remove it. For many contaminants of concern, these parameters are well known. However, petroleum products may consist of many components with a wide range of physical properties. Laboratory analysis of soil or NAPL samples is often used to determine the distribution of contaminants. A field pilot test is performed to estimate vapor offgas concentration in the initial stages of the remediation.

3.2.2 Pilot Testing

Pilot tests are commonly performed at sites where a large area is to be treated or where the response to vapor extraction cannot be predicted with confidence. In practice, most sites are subject to at least a short-term pilot test, but systems for very small sites where the geology is known to be amenable to vapor extraction are sometimes designed without a pilot test.

Pilot testing is typically the first step in moving from a conceptual design to a final design. A conceptual design is always developed prior to pilot testing from an understanding of site conditions based on site investigation results. The pilot test and site investigation are inextricably linked — the pilot test is performed and interpreted in light of preceding site investigations, and the site investigation is reevaluated in light of the pilot test results. The results of the pilot test and site investigation lead to an understanding of the site and the ultimate vapor extraction design concept. Evaluation of the pilot test results then culminates in a preliminary design.

The primary objective of vapor extraction pilot testing is to provide information on soil permeability and offgas contaminant loading so that effective vapor extraction and offgas treatment systems can be properly sized. In many cases, this information can be obtained from a short-term pilot test requiring only a few hours and involving measurement of only the applied and vadose zone vacuum, recovered soil gas flow rate, and composition of the blower offgas. However, short-term pilot tests have their limitations and may be incapable of achieving other objectives, such as those related to bioremediation and dual-phase extraction. Therefore, longer term tests should be considered for the following situations:

- The site has a deep vadose zone or a tight surface seal or is highly stratified. In such cases, it may take more than a few hours for the system to reach steady-state conditions.

- Contaminant fate information, typically in the form of soil or soil gas samples collected before and after operation of vapor extraction is needed. Permanent substantial changes in these parameters can be expected only after weeks of operation.
- Detailed information on offgas composition is required. The initial VOC, O_2, and CO_2 concentrations in the offgas usually change gradually over time, so evaluation of long-term volatilization and biodegradation rates for offgas treatment sizing and prediction of remedial performance may require a longer pilot test.
- Treatment is to occur within a low-permeability, high residual water saturation formation with a high vacuum, such as is typically done in dual-phase extraction. The relative air permeability can change dramatically as soils are dewatered by the high vacuum, resulting in significant changes in system performance over the course of weeks or months.

The following sections discuss the setup, execution, and data acquisition requirements for conventional vapor extraction pilot tests (Section 3.2.2.1); high-vacuum, dual-phase, bioslurping pilot tests (Section 3.2.2.2); and bioventing pilot tests (Section 3.2.2.3).

3.2.2.1 Conventional Vapor Extraction Pilot Tests

Pilot-scale activities for vapor extraction focus on in situ measurement of parameters that facilitate the estimation of soil permeability to vapor flow, volume of soil in which vapor extraction occurs, extracted vapor concentration and composition, aerobic biodegradation rates (if contaminants are aerobically biodegradable), and requirements for combination injection/extraction systems and flow balancing. Vapor extraction pilot testing requires a minimum test system consisting of the following:

- test vapor extraction well screened within the contaminated soil;
- blower to induce air flow;
- vapor treatment system (if required);
- calibrated flow and vacuum measurement devices; and
- in situ vadose zone monitoring installations.

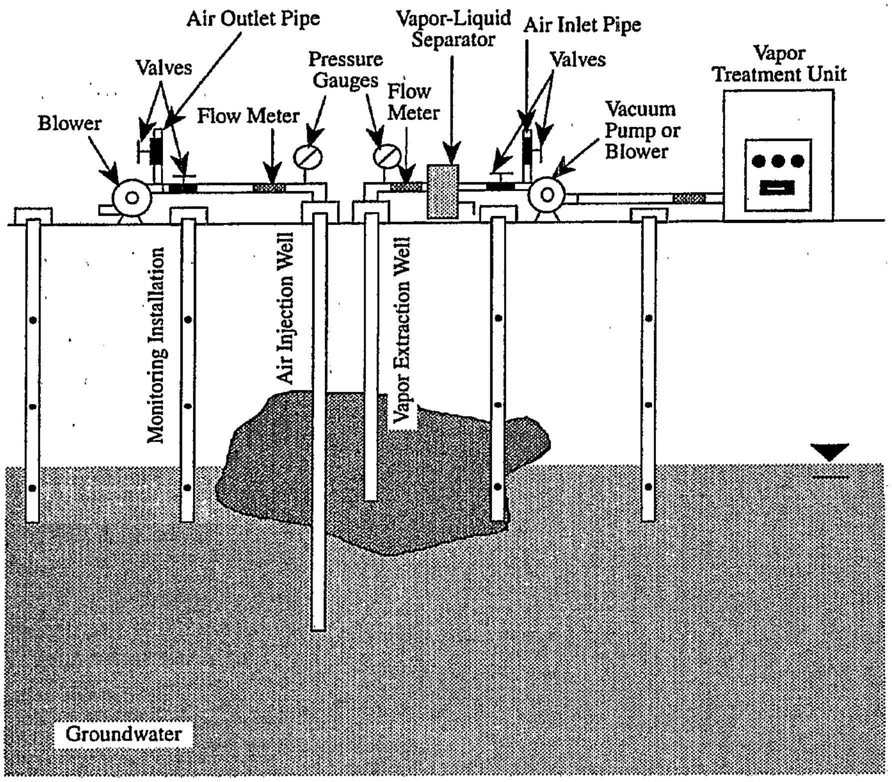
Depending on the information desired, additional characterization activities may also require the following:

- sampling ports in the process lines;
- gas sampling devices (sampling pumps, syringes, etc.);
- analytical instruments (hydrocarbon analyzer, gas chromatograph, respiration gas analyzer, etc.);
- tracer gas delivery system and monitoring system; and
- groundwater level monitoring device.

Pilot vapor extraction wells should be placed within the area to be treated by the full-scale system. This typically means that extraction wells are placed within the contaminated soil zone and screened so as to induce air flow through or past (in the case of highly heterogeneous media) the zone containing contaminants. 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 pilot test well is appropriate. In practice, existing groundwater monitoring wells are often used for pilot-scale testing; however, this is appropriate *only* in cases where the capillary fringe area is the zone of interest and *only* if the monitoring well is properly screened in the contaminated portion of the vadose zone and within a single soil zone. Otherwise, pilot tests conducted with these wells may not be representative of full-scale operation.

Care should be taken in locating flow meters and pressure gauges with relation to the blower. Since most blowers are driven by fixed-speed motors, extraction flow rates are often controlled by installing gate, block, and/or globe valves and an air inlet and outlet pipes on the manifold as shown in Figure 3.1. Although a single in-line valve is sufficient to control the extraction flow rates, the air inlet and outlet pipes are typically included to allow the same level of control, while also preventing the blower from overheating. Flow meters and pressure/vacuum gauges should be placed between the wellhead and the first encountered valve or piping junction, otherwise the flow rate and applied vacuum at the wellhead cannot be measured accurately. Unfortunately, these measuring devices are often incorrectly located between the blower/vacuum pump and an air inlet/outlet valve resulting in inaccurate data.

Figure 3.1
Simplified Field Pilot Test Schematic for Vapor Extraction-Based Technologies



Source: Johnson et al. 1994

Vapor Flow vs. Applied Vacuum Test or "Step Test". To estimate air permeability and select an appropriate vapor extraction blower/vacuum pump for the full-scale system, extraction flow rates should be measured during the pilot test as a function of applied vacuum for each test well. This relationship can be established by conducting a "step test". For a pilot-test system connected as shown in Figure 3.1, a step test is accomplished through the following procedures:

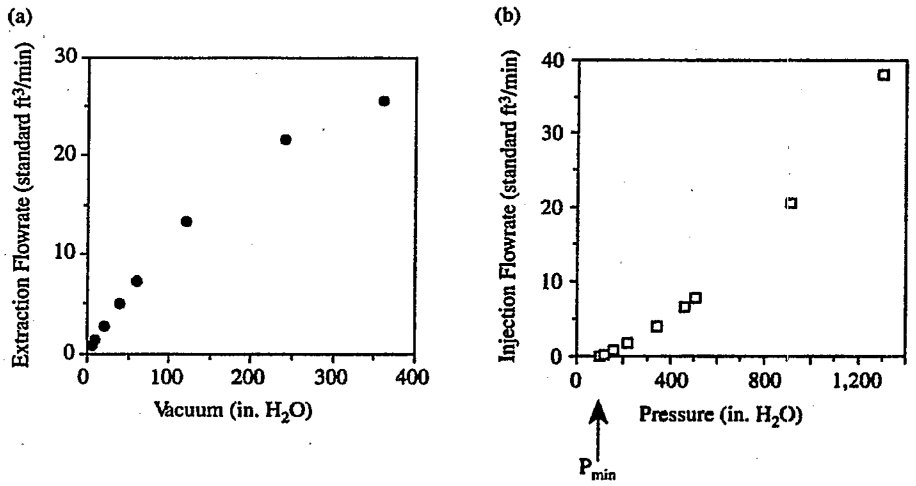
1. Open the air inlet valve.
2. Close the valve leading to the wellhead.

3. Turn on the blower/vacuum pump so that air is drawn in through the air inlet line only.
4. Fully open the valve leading to the wellhead.
5. In one step, or optionally in a series of increments, slowly close the air inlet valve until fully closed.
6. For each increment, allow the flow rate to stabilize (this may take several minutes or several hours, depending on soil permeability) and record the wellhead vacuum and flow rate.

The extraction step test can usually be conducted within a few hours since flow rates typically stabilize (for all practical purposes) fairly quickly. Data from these tests are usually presented as shown in Figure 3.2. These methods are recommended only; there are other acceptable methods of displaying the data. Flow rates should be reported in "standard" flow rate units, as discussed in Section 4.4.1.

Figure 3.2

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



Source: Johnson et al. 1994

Extracted Vapor Characterization vs. Time. When evaluating vapor extraction, air sparging, bioventing, or any other variation of the technology, the extraction vapor concentrations and compositions observed during pilot testing provide a basis for vapor treatment design. The pilot information, along with knowledge of possible extraction well flow rates and regulatory requirements, can be used to determine what process modifications (vapor treatment units or lower flow rates) are necessary to comply with emission requirements.

Extracted vapor quality data can be collected during or following the extraction step test discussed above. There are three common methods of measuring contaminant vapor concentrations as a function of time: (1) use of a field total hydrocarbon analyzer (flame ionization detectors [FIDs] or photoionization detectors [PIDs]; (2) use of an on-site portable gas chromatograph; or (3) collection of vapor samples in sampling bags or Summa canisters with subsequent gas chromatographic analyses at an off-site laboratory. Regardless of the method chosen, at least a few samples should be sent to an off-site laboratory for confirming analyses.

Typically, in-field screening is performed using a FID, a PID, or a combination PID/FID instrument. A PID will not detect methane and will respond differently to various types of hydrocarbons (a FID will detect methane). For this reason, at sites contaminated with mixtures of nonhalogenated organics, such as fuels, a combination PID/FID field instrument is the recommended field screening device.

In the absence of chromatographic separation, the total PID or FID response is used as a screening level 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. Field-screening PIDs or FIDs are inexpensive and easy to use, but no compound-specific data are available, and the sensitivity of these instruments can change significantly for a particular compound depending on such factors as vapor contaminant composition, temperature, pressure, and water content of the vapor. Thus, the PID, and to a lesser extent the FID, is a poor indicator of total contaminant concentrations and should not be used for this purpose unless it is known that a single component dominates the vapor or that the instrument is equally responsive to all compounds in the vapor stream. A PID or FID usually works best when a single compound is present and its response is known. A "hot wire" detector is used to monitor explosive vapors and is adequate for monitoring total contaminant response at higher concentrations (above 100 ppm_v).

It is important to recognize that expression of gas concentrations in volume/volume units is meaningless unless the calibration compound is also specified. 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).

On-site gas chromatographs (GCs) are valuable since compound-specific composition of the vapor stream can be determined at the site in near real-time. Even though the sample analysis process is simple, these instruments should be only operated by knowledgeable personnel because troubleshooting and identifying erroneous results requires a thorough understanding of the underlying principles of gas chromatography. It should be noted that portable GCs typically cannot accurately quantify very volatile compounds such as vinyl chloride and may not be able to separate all compounds of concern, such as *cis*- and *trans*-1,2-dichloroethene.

Perhaps the most common approach to monitoring extracted vapor hydrocarbon concentrations is to take readings with a PID/FID instrument in the field at regular intervals throughout the pilot test and also to collect vapor samples periodically for off-site GC analysis. This approach allows for monitoring general trends in total contaminant concentrations while also determining the individual compounds present in the vapor at select times throughout the test.

For sites contaminated with fuels of unknown origin, it may be useful to perform *boiling point analyses*. The results of these analyses show the composition of a vapor sample with regard to carbon chain length, which is related to the volatility of the vapor species. Conducting a boiling point analysis on a sample of the fuel will provide an indication of the fraction of the fuel that will volatilize under vapor extraction conditions. Boiling point analyses conducted on a vapor sample during a pilot test will establish the baseline with which samples collected during full-scale operation can be compared. A comparison of the relative attenuation of various fractions over the course of remediation lends insight into the fraction of material removed by vapor extraction and can be used to extrapolate remediation time.

Although a particular vapor extraction system may not be intended to be a bioventing system per se, respiration gas concentrations should be measured in the extracted vapor stream if the site contaminants are aerobically biodegradable. In addition, in situ biorespiration tests (described in Section 3.2.2.3) should also be performed. Such tests should be conducted because under conditions that are favorable to aerobic biodegradation, the amount of contaminant mass removed by biodegradation resulting from soil aeration induced by vapor extraction operation may easily surpass the mass removed by physical processes, especially for heavier petroleum distillates and during the later stages of remediation. Monitoring of respiration gases and performance of in situ respiration tests provide data to estimate the mass removal due to biodegradation.

Respiration gases are most effectively and simply measured by field infrared gas analyzers equipped to measure oxygen, carbon dioxide, and methane. These instruments provide simultaneous, real-time readings for all three gases.

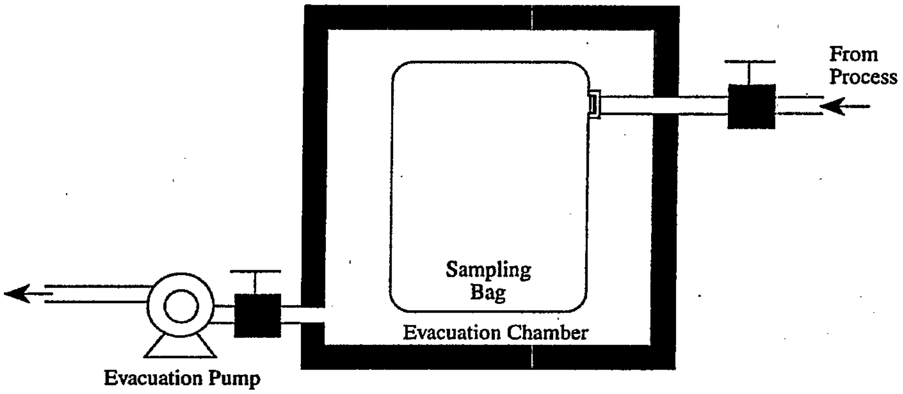
Although collection and analysis of vapor samples is not complicated, the following measures should be incorporated into any pilot test sampling plan:

1. Samples should be collected between the extraction wellhead and any air inlet line.
2. The test should be conducted for a long enough period to ensure that vapor concentrations are representative of extended system operation; vapor samples should be collected after extractions of several pore volumes of soil gas.
3. Periodic monitoring of air treatment (e.g., carbon filter) exhaust should be completed to ensure explosive conditions within any air treatment equipment are noted and managed appropriately.

The first measure ensures that representative samples of the extracted vapors are obtained. Sampling ports should not be placed within a few feet of any air inlet junction as significant back-mixing may occur near the junction. Since vapor samples are being withdrawn from a system under vacuum, this vacuum must be overcome to collect a sample. The recommended sampling procedure is to drag 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. Bag samples can be obtained by pumping gas directly from the wellhead into a sample bag using a manual or automated sampling pump. However, a superior sampling method is depicted in Figure 3.3. 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 passing through a sampling pump.

Figure 3.3

Schematic of Apparatus for Sampling Vapors Under Vacuum Conditions



Source: Johnson et al. 1994

The second measure is important because samples obtained at the start of an vapor extraction pilot test are not representative of sustained full-scale system operation. Typically, when flow is initiated in a pilot test, the relatively high extracted vapor concentrations decrease rapidly 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 sustained operation of the system. Consequently, it is useful to estimate how long a given test must be conducted. Johnson and Stabenau (1991) have presented the following approach, which approximates this transient period $\tau_{startup}$ (in seconds) as the time required to sweep one "pore volume" of vapors through the flow zone:

$$\tau_{startup}(t) = \frac{\varepsilon_A \pi R_F^2 H_F}{Q_{well}} \tag{3.1}$$

where: ε_A = the air-filled void fraction in the subsurface (0.30 is a good estimate for most unconsolidated soils);

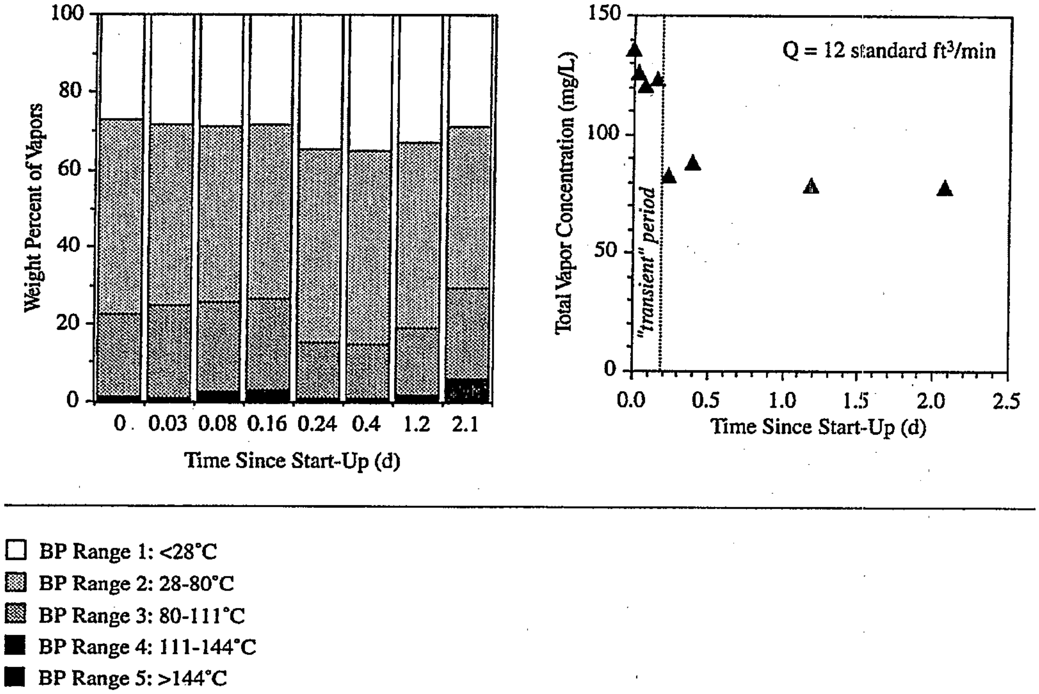
Q_{well} = the volumetric flow rate to the extraction well (cm^3/s);

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, Johnson and Stabenau recommend that R_F be estimated to be roughly equal to the depth to the top of the screen for the well (H_F). For an extraction well screened from 3 to 4 m (10 to 15 ft) below ground surface (bgs) pulling 0.01 m^3/s (20 standard ft^3/min), Equation 3.1 predicts the transient period to last approximately 50 minutes. Data collected during this test can be reduced and displayed as shown in Figure 3.4.

As mentioned in Section 3.2.1, when conducting vapor analyses in the field, it is important to confirm and augment the field results with off-site laboratory analyses using the TO-12 and/or TO-14 methods. Off-site analysis, while more expensive and lacking the immediacy of field analysis, is generally more accurate and can often better identify the individual sample components.

Subsurface Vapor-Phase Pressure Distribution. The subsurface pressure distribution in the vadose zone resulting from vapor extraction pilot test operation should always be monitored. This information is used, along with the vacuum/flow response information, to assess the air permeability and/or the relative horizontal-to-vertical permeability ratio in the soil in the vicinity of the test well. The zone of influence for the test well is determined from this permeability information and can be used along with permeability distribution data and vapor flow modeling results to gain a better understanding of the subsurface vapor flow patterns. Pressure distribution is commonly measured only as a function of radial distance from the vapor extraction well. This is usually adequate, but better results are obtained when the pressure distribution evaluation also includes the vertical dimension, especially at stratified sites where soil permeability varies substantially with depth.

Figure 3.4
Presentation of Extracted Vapor Analyses from Pilot Test

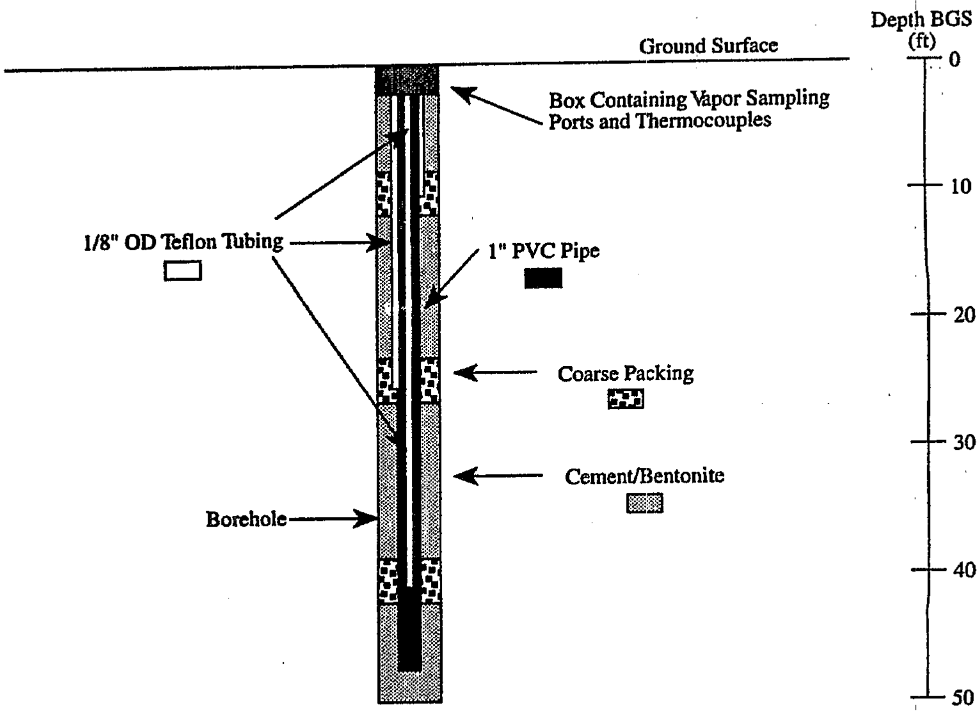


Adapted with permission from Johnson et al., "Soil Venting at a California Site: Field Data Reconciled with Theory", *Hydrocarbon Contaminated Soils and Groundwater*, Volume 1, 1991, P.T. Kostecki and E.J. Calabrese (eds.). Copyright CRC Press, Inc., Boca Raton, FL.

Vertical changes in vacuum give an indication of the leakiness of the surface and the vertical/horizontal air permeability ratio. The pressure distribution is estimated by measuring the soil pressure at various distances from the test well, preferably also at discrete depth intervals. Generally, the most cost-effective method of installing pressure monitoring points is to use a direct-push unit (i.e., Geoprobe). Direct-push installed vadose zone points consist of small-diameter polyethylene tubing attached to a drive point that is driven into the subsurface to the desired depth. Care should be taken during the installation of shallow (less than 1.5 m [5 ft]) driven points as leakage or short circuiting is possible. Direct-push vapor monitoring point installation is best for applications involving shallow installation depths and granular soils. Installation at depths greater than 15 m (50 ft) can be problematic, and direct-push probes can rarely penetrate cobble or cemented layers in soil.

Figure 3.5 depicts an example of a tri-level pressure monitoring point installation. Existing groundwater monitoring wells can be used as pressure monitoring points if the screened interval is at least partially exposed to the vadose zone. However, this approach alone rarely provides a vertical profile of pressures, which can be beneficial at sites with distinct strata of soils with substantially differing permeabilities.

Figure 3.5
Tri-Level Pressure Monitoring Point Installation



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Vadose zone monitoring points should be placed over the full range of the expected zone of extraction, with at least one well very close to the vapor extraction well. For example, monitoring points located at approximately 1.5, 3, 7.5, 15, and 23 m (5, 10, 25, 50, and 75 ft) from the extraction well may be needed depending on soil permeability and degree of heterogeneity. If vertical profiling of soil pressures is also to be evaluated, three levels, or at least one point in each distinct soil stratum, should be installed. In addition, in heterogeneous soils, monitoring points should be placed in at least three different directions from the test well to better define the soil pressure distribution and identify regions that may not have significant vapor flow.

The step test described previously presents an opportunity for measuring soil pressure distributions at a given extraction vapor flow rate. There are two types of soil pressure data that can be collected during the pilot test: transient data and steady-state data. Steady-state data are much easier to acquire and, in most cases, are adequate to evaluate soil permeabilities and the horizontal-to-vertical permeability ratio. In fact, it may not be practicable to collect transient data in very permeable soils (medium to coarse sands) without a robust and extensive surface seal, as the flow field is established within a short period.

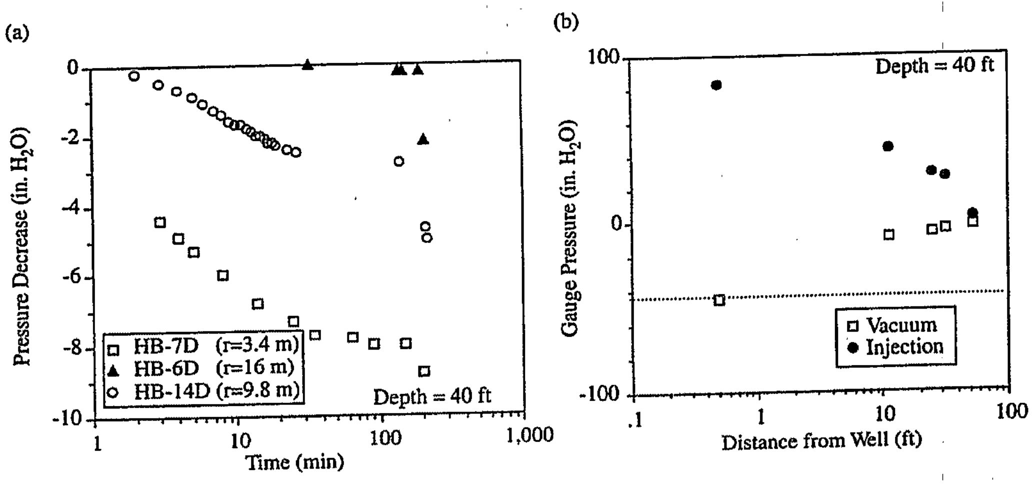
Transient data may be required in cases where the vadose zone is deep (on the order of 30.5 m [100 ft] or more), where the vadose zone is highly stratified, and/or where a robust and extensive surface seal exists (such as an airport). Transient data are often presented as shown in Figure 3.6a. The presentation of steady-state data varies, depending on the density of sampling points. For sparse data, the presentation is usually similar to that of Figure 3.6b.

3.2.2.2 High-Vacuum Vapor Extraction, Dual-Phase Vapor Extraction, and Bioslurping Pilot Tests

The objectives for pilot testing of high-vacuum, dual-phase, and bioslurping vapor extraction applications are dramatically different from those described in Section 3.2.2.1 for conventional vapor extraction. The high vacuum used in these applications often results in a gradual drying of the vadose zone soil as pore water is mobilized by pressure gradients. The vapor extraction well essentially acts as a large vacuum lysimeter, removing soil moisture from the vadose zone. As the water saturation of the soil decreases, the air saturation increases, often resulting in a substantial increase in air permeability of the soil after several weeks or months of operation.

Figure 3.6

Presentation of Subsurface Pressure Monitoring Results from Pilot Test — (a) Transient Results, (b) Steady-State Results



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Therefore, steady-state conditions are reached only after a long period of operation — much longer than the duration of most high-vacuum pilot tests.

As an alternative to pilot testing for high-vacuum, dual-phase, and bioslurping applications, phased implementation may be more appropriate. At a large site with low-permeability soils where one of these approaches is anticipated, several wells may be installed initially and operated for a period of several months. Following review of the performance of these wells, the full-scale system would then be installed. Obviously, at a small site, the preliminary system would address the whole site, and adjustments (e.g., additional wells to provide tighter spacing, greater blower capacity, etc.) would be made to the system after a few months of operation, rather than expansion of the preliminary system into other areas.

Because of the time required to achieve steady-state conditions, and because high-vacuum, dual-phase, and bioslurping applications are generally practiced at the highest vacuum attainable, testing of these applications is generally performed at a single vacuum. This contrasts with conventional vapor extraction tests, where step tests at several vacuum levels may be performed. In addition, the pilot test equipment required for high-vacuum, dual-phase, and bioslurping tests obviously will be different from that required for conventional vapor extraction tests since higher vacuums are applied and LNAPL and extracted groundwater must be separated from the vapor stream and managed. In addition to the vapor extraction pilot parameters previously described, the following should also be collected during the pilot test for high-vacuum, dual-phase, and bioslurping systems:

- water recovery rate vs. time;
- total mass removal vs. time;
- NAPL recovery rate vs. time;
- distribution of contaminant mass removed as aqueous product, vapor, and NAPL; and
- recovered water quality and need for treatment.

3.2.2.3 Bioventing Pilot Tests

Each of the parameters described under vapor extraction pilot testing (soil permeability, extraction/injection zone of influence, and step test results) should also be measured for a bioventing pilot test. In addition, in situ respiration tests must be performed to confirm that subsurface conditions are favorable for biodegradation and to estimate the average biodegradation rates that can be expected under full-scale operation.

Hinchee et al. (1992) have developed a detailed test protocol for in situ respiration testing for the U.S. Air Force that has been used at many bioventing sites in the Unites States. This protocol is available in a document entitled, *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing*. In addition, the *WASTECH*® monograph, *Bioremediation,* gives a detailed description of this testing (Dupont et al. 1998). A brief summary is provided here.

After establishing baseline oxygen and carbon dioxide vapor concentrations in the test wells, air is injected which contains an inert tracer gas (usually, 1-2 volume % helium) into the vadose zone. An area of highest VOC contamination and an uncontaminated location having similar soil properties are usually selected. The air provides oxygen to the soil and the helium provides diffusivity data that can be used to estimate the diffusion of oxygen from the ground surface. After some period of time, typically 24 hours, gas injection is stopped, and concentrations of oxygen, carbon dioxide, and helium are monitored periodically over several days. Alternatively, the soil gas sampling for oxygen and carbon dioxide may be performed after an extended period of vapor extraction, such as at the end of a 24-hour pilot test. The respiration gas concentrations should be monitored in several vadose zone monitoring points like those used for soil pressure readings as described in Section 3.2.2.1. It is imperative that the soils around the point being monitored (1) are contaminated, and (2) have been adequately aerated by operation of the air injection or by the vapor extraction system. Initial oxygen concentrations in soil gas should be at least 15% (by volume) and more desirably 19 to 21%. Respiration gas concentrations should be monitored at appropriate time intervals to adequately define the oxygen utilization rate until the oxygen concentration declines to about 2%.

At least one respiration test should also be conducted in a "background" area to assess the rate of any "natural" subsurface oxygen-utilizing processes. Ideally, the background area is similar with regard to geological and microbial conditions and differs only in that no contaminants are present. Interpretation of in situ respiration test data is discussed in Section 3.2.3.4.

3.2.3 Pilot Test Results Interpretation

Interpretation of pilot test results usually involves extracting values for air permeability (k_a), the horizontal-to-vertical permeability ratio (k_h/k_v), and sometimes the surface permeability (k_s). These values are then input into an air flow model to determine the spacing and operation of extraction (and sometimes injection) wells such that the air flow provided throughout the contaminated zone is adequate to effect the required remediation in the desired time frame. The goal of interpretation of the pilot test results is the evaluation of air flow paths, and the permeabilities are intermediate parameters calculated during this exercise. In fact, it is possible to evaluate air flow paths directly without explicitly solving for the air permeabilities (Bass 1993a), but in practice, the intermediate step of solving for permeabilities is usually taken.

3.2.3.1 Evaluating Air Permeabilities

A variety of models are available to determine k_a from pilot test data. Many of these models also can evaluate k_h/k_v and/or k_s. All provide values for k_a that are averaged over the soil conditions in the immediate area of the extraction well. Changes in location may result in different values for k_a, as will changes in soil water saturation over the course of remediation (of particular concern in high-vacuum and dual-phase applications).

One-Dimensional Radial Flow Solutions. One-dimensional radial flow solutions have been developed by McWhorter (1990) and Johnson et al. (1990), among others. McWhorter's solution consists of preparing a graph of the square of the absolute pressure in the subsurface at distance (r) from the extraction well, normalized to atmospheric pressure $(P/P_{atm})^2$ versus the log of the distance from the extraction well squared divided by the time since the start of the test ($\ln[r^2/t]$) and using the slope of the resulting line in the appropriate equation in Appendix A. Johnson's solutions can be evaluated for k_a by plotting gauge pressure in the subsurface at distance (r) from the extraction well ($P - P_{atm}$) vs. the log of the time since the start of the test ($\ln\{t\}$) and using the slope of the resulting line from the equation in Appendix A. Johnson's approach has been implemented in the popular "Hyperventilate" and "VENTING" design tools.

Because of the simplifying assumptions of one-dimensional radial flow solutions, these methods should be used *only* for sites with an impermeable surface seal where the entire vadose zone is to be addressed by vapor extraction. Few prospective vapor extraction sites meet these criteria (Beckett and Huntley 1994), as surface infiltration of air is the rule, rather than the exception. For this reason, the subsurface vacuum field at most vapor extraction sites rapidly achieves steady-state conditions, and the time-dependent subsurface pressure data necessary for McWhorter's and Johnson's analyses are difficult to obtain.

Two-Dimensional Radial Flow Solutions. Models of this type, which can account for surface infiltration and vertical anisotropy, have been developed by Shan, Falta, and Javandel (1992), Joss and Baehr (1995a), and Falta (1996)(see Appendix A). There are no "cookbook" methods for regression of pilot test data using this type of model to determine permeabilities. A computer program must perform iterations until the permeabilities best fit the field data. Unlike the one-dimensional radial flow solutions, the two-dimensional solutions provide estimates of k_h/k_v in addition to k_a. Furthermore, Joss and Baehr's solution will also estimate k_s. Joss and Baehr's solution has been implemented in "AIR2D," a Fortran program available from the U.S. Geological Service.

Two-dimensional radial flow solutions can be used for virtually any site conditions. They assume steady-state operating conditions and therefore, do not require time-dependent subsurface pressure data. At most sites, where steady-state is reached rapidly, this makes pilot test data collection much easier and less expensive. However, at the occasional site where a tight surface seal does exist (e.g., beneath the hardstand at an airport), steady-state conditions may require days to establish. In such cases, pilot test duration may be reduced by taking transient subsurface pressure data and using a one-dimensional radial flow solution for the analysis. The disadvantage to this approach is that vertical anisotropy cannot be evaluated.

To make optimum use of the capabilities of two-dimensional radial flow models, subsurface vacuum should be measured at various depths within the vadose zone, as well as at various distances from the vapor extraction well. In many cases, this means that a substantial number of new vapor monitoring points will have to be installed for the pilot test.

3.2.3.2 Evaluating Other Parameters from Pilot Test Data

The US ACE (1995) describes a number of additional analyses which can be performed on pilot test data.

Vent Well Efficiency. Head losses between the vapor extraction well and the subsurface soil can lead to underestimates of k_a. When vent efficiency (defined as the ratio of the vacuum just outside the test well to the applied vacuum) is low, the conventional semilog plot of subsurface pressure versus distance from the extraction well is shifted downward (the applied vacuum appears to be lower than it actually is), although the shape of the curve does not change. Therefore, estimates of k_a (which is intercept-dependent) are affected, although estimates of k_h/k_v (which is slope dependent) are unaffected.

Vent efficiency can be estimated from direct measurements of vacuum dissipation in the well annulus by installing a small-diameter piezometer in the annulus of a vertical vent well or within a few centimeters of the vent well borehole. Also, nesting a piezometer increases the risk of well seal failure. Separate piezometer installations within a few centimeters of the borehole are also problematic and carry additional expense.

A more practical method for estimating vent efficiencies is to compare the applied vacuum in the test well to the theoretical vacuum predicted by steady-state radial flow models. In most cases, a two-dimensional model will be necessary for this comparison, and this will require computer iteration to find the vent well efficiency that best fits the observed data. In rare cases where a surface seal exists, a one-dimensional model can be used and simple, explicit equations for vent well efficiency can be applied (Appendix A).

In most cases, the variability in k_a among vapor extraction wells will be greater than the variation in well efficiency. The effect of well efficiency will cancel out in any case, because the pilot test well will generally have a well efficiency similar to the extraction wells in the full-scale system. Investigations of well efficiency would be necessary only if an existing monitoring well of questionable construction was used for the pilot test and if the results deviated significantly from what was expected. Typically, a semilog plot of subsurface pressure versus distance from the extraction well will intercept the y-axis at 10 to 30% of the applied vacuum, reflecting a well efficiency of around 50%. If such a plot has a y-intercept of less than 10% of applied vacuum, poor well efficiency may be suspected.

Air Saturation. US ACE (1995) cites the use of a one-dimensional radial flow solution to estimate air-filled porosity. Air saturation can also be measured directly from laboratory analysis of an undisturbed soil sample. When air saturation is low, air permeability is also low. Over the course of vapor extraction operation, especially when high vacuum is employed, air saturation may increase, leading to a dramatic increase in k_a. Estimates of this effect may be made using the soil moisture retention curve or a field method such as a neutron probe. However, k_a is so sensitive to small changes in air saturation that precise estimates of the increase in permeability over the course of vapor extraction operation are generally impractical.

Upwelling. Groundwater within the vapor extraction well is drawn up the well by the applied vacuum. This has the effect of reducing the amount of exposed well screen, and as the recovered soil gas is forced to pass through smaller amounts of open area, the high velocity can entrain water into the air stream and along the walls of the extraction well, resulting in water handling problems at the surface. In some cases, upwelling leads to the paradoxical result of an increase in applied vacuum, resulting in a lower rate of soil gas recovery. Upwelling also reduces the magnitude of air flow in the lower portions of the vadose zone, which is where the greatest contaminant concentrations are often found. Upwelling can be monitored by placing a pressure transducer in the extraction well and comparing the head difference when the vapor extraction system is on and off (Appendix A). Alternatively, a bubbler tube can be installed in the vapor extraction well at a estimated known elevation and sealed through the well cap. Water levels in the well can be determined by measuring the pressure required to initiate a flow of air through the bubbler tube.

The vacuum applied to the top of an extraction well is often the same as the vacuum at the bottom of the well. Exceptions occur with high flow rates in deep extraction wells, or in small-diameter (< 2 in.) extraction wells. Pressure drop along the length of a vapor extraction well has been addressed by Bass (1992), Skomsky and Fournier (1996), and McPhee, Bass, and Mott-Smith (1997), among others. So long as these conditions do not occur, it is a safe assumption that, at steady-state, the upwelling within the vapor extraction well will be nearly equal to the applied vacuum expressed in height of water column, provided significant entrainment of groundwater into the air stream is not occurring.

Field Criteria for Vapor Extraction Feasibility Screening. Peargin and Mohr (1994) have developed pass/fail criteria for estimation of vapor extraction feasibility based on a comparison of field subsurface vacuum measurements with the results of a numerical two-dimensional radial flow solution. The solution is plotted using normalized variables with the log of subsurface pressure (expressed as a percent of applied vacuum at the vapor extraction well) on the vertical axis and distance from the extraction well (expressed as multiples of vadose zone thickness) on the horizontal axis. Field data are then superimposed on this plot. When the data fall largely below the numerical solution with $k_h/k_v = 1$ (i.e., the horizontal permeability is apparently less than the vertical permeability), then the site is probably unsuitable for vapor extraction.

Peargin and Mohr's approach is simple yet elegant, and cookbook judgments can be made quickly by junior staff using this approach. An apparent k_h/k_v significantly less than one can often reflect conditions unsuitable for vapor extraction, such as vertical fracturing of soil (common in clays) and preferential pathways leading to short circuiting. However, some well conditions, as well as site conditions, can also lead to negative results. A poor well seal on the extraction well or monitoring points or poor extraction well efficiency will lead to an apparently low k_h/k_v, and in high-vacuum applications, the response of the soil may change considerably with time as system operation progresses. Therefore, an evaluation by experienced technical personnel is advisable before a final judgement is reached.

3.2.3.3 Evaluating High-Vacuum and Dual-Phase Pilot Test Data

Pilot tests for high-vacuum and dual-phase extraction of low-permeability soils often must be longer because the air permeability of the soil changes as moisture is removed, and steady-state conditions may not be reached for weeks or months. This effect can be estimated by measuring the soil moisture retention curve from an undisturbed sample in the laboratory and interpreting short-term pilot test data in light of this measurement. However, k_a is so sensitive to small changes in air saturation that precise estimates of the increase in permeability over the course of vapor extraction operation are generally impractical. Therefore, from the standpoint of evaluating air flow, it often makes the most sense not to perform a pilot test when the treatment area is limited. Alternatively, a full-scale system can be installed and modified based on its performance over the first few months of operation. As discussed in Section 3.2.2, long-term pilot tests or phased implementation is still appropriate for large systems where cost considerations dictate that mid-course corrections be minimized.

Short-term pilot tests for dual-phase applications may be useful for evaluating groundwater recovery and drawdown parameters. Traditional methods for evaluating hydrogeologic parameters are used, except the apparent drawdown in the extraction well is the sum of the water table depression and the applied vacuum expressed in height of water column.

Evaluating Bioventing Pilot Test Data. This section is adapted with permission from *Soil Vapor Extraction and Bioventing — Engineering and Design* (US ACE 1995). Additional information on bioventing pilot testing and interpreting results can be found in the AFCEE document entitled *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing* (Hinchee et al. 1992).

The concentrations of subsurface oxygen and carbon dioxide measured during an in situ respirometry test are plotted against time, and the rate of oxygen consumption (the initial slope) is expressed in terms of percent/day.

The biodegradation rate is usually calculated assuming hexane to be representative of hydrocarbons in the soil. The biodegradation rate is estimated as:

$$K_B = -0.01 K_O A D_O C \tag{3.4}$$

where: K_B = biodegradation rate (mg hexane/kg soil • day);
K_o = oxygen utilization rate (percent/day);
A = volume of air per mass of soil (L/kg);
D_o = density of oxygen gas (1,380 mg/L at 50°F and 1 atm); and
C = stoichiometric mass ratio of oxygen to hydrocarbon (3.53 for hexane).

3.2.4 Preliminary Design Based on Full-Scale Air Flow Analysis

Once the various permeabilities of the soil and ground surface have been evaluated, these values can be input into a model to determine the number and spacing of vapor extraction wells, the applied vacuum, and the anticipated soil gas extraction rate. These parameters are highly site-specific and depend on depth of contamination, physical and chemical properties of contaminants, soil characteristics, and air permeability. These parameters are also interrelated; as applied vacuum is varied, the flow and effective radius of influence also change. Therefore, system design is an iterative process.

Typically, the engineer begins by selecting a set of operating conditions that includes a high applied vacuum and soil gas extraction rate (for a single well). At this stage, the diameter of the vapor extraction wells will typically be assumed to be 2 inches in this initial design. At these conditions, the effective radius of influence for remediation is then evaluated, and the number, spacing, and placement of wells on the site are determined accordingly. The soil gas extraction rate for the entire system is then identified, and an overall system cost is calculated.

In general, decreasing the applied vacuum will decrease the life cycle cost for the final system since the reduced air handling and treatment costs will outweigh the incremental drilling and piping costs for more wells. Therefore, the next step in the design process is to reduce the applied vacuum and repeat the evaluation of radius of influence and computation of system cost. This process is repeated until the incremental cost savings from reduced air handling reaches a point of diminishing return when compared with the additional drilling and piping costs.

At this stage in the design process, the engineer may also wish to evaluate variations of vapor extraction technology, such as air injection wells, horizontal wells, vented trenches, thermal enhancement, or hydraulic fracturing.

3.2.4.1 Evaluating Radius of Influence for a Single Extraction Well

The primary goal of vapor extraction is to provide sufficient air flow through contaminated soil to remediate the soil within a desired time frame. For bioventing systems, the goal is to provide adequate air flow to prevent oxygen deficiency from being a limiting factor in bioremediation. Well spacing, based on an assumed radius of influence, is chosen with these goals in mind.

Historically, radius of influence has been evaluated by plotting the log of subsurface pressure ($\ln\{P\}$ or $\log_{10}\{P\}$) versus distance from the extraction well (r), regressing, and extrapolating or interpolating the regression line to an arbitrary pressure value, typically ranging from 0.025 to 2.54 cm (0.01 to 1 in.) water column (some practitioners have extrapolated to a percentage of applied vacuum, typically 1%). The radius of influence evaluated in this way is arbitrary since the vacuum cutoff level is arbitrary. Furthermore, subsurface vacuum does not necessarily reflect subsurface air flow, and it is the air flow that effects remediation. Focusing on vacuum rather than flow gives a radius of influence that is insensitive to the volatility of the contaminant, the permeability of the soil, the required extent of remediation, and the desired remedial time frame.

Many alternative approaches have been developed that focus on air flow. All are more rigorous than the vacuum cutoff method and give more meaningful results, but most are also more difficult to use. Flow-based models determine how far from the extraction well sufficient air velocity can be effected to achieve the required remediation within the desired time frame. Flow velocity is generally expressed in terms of pore-volume exchanges. The less volatile the contaminant, the greater the number of pore-volume exchanges required, at least until the system becomes diffusion-limited. The required air throughput is dependent on the initial soil concentrations (lower concentrations require less air). Also, mass transfer kinetics can affect the efficiency of the removal; the optimum well spacing may change over time, since in the later stages of remediation, removal of the remaining contaminants from soil moisture and dead-end pores may be transport-limited.

The same model used to develop an effective radius of influence should generally be used to determine permeabilities. All methods for estimating permeability will incur some error due to modeling assumptions, but if the same model is used to determine radius of influence, some of this error will cancel out. In fact, it is theoretically possible to evaluate effective radius of influence directly from pilot test data, without intermediate calculation of permeabilities (Bass 1993a).

Estimating radius of influence using a one-dimensional radial flow solution is somewhat problematic because assuming a perfect seal both at the surface and at groundwater means, mathematically, that there is no source for air and steady-state can never be achieved. A radius of pressure influence must therefore be assumed, reflecting a phantom air source at some distance from the extraction well. The air flux can then be calculated within this distance from the well, and the distance at which sufficient air flow is achieved can be determined. This approach works well when a good surface seal exists and when air injection wells are used (approximating the phantom air source). However, the approach will overestimate effective radius when no surface seal is present since the model's presumption that all of the soil gas recovered has passed through all of the contaminated soil is invalid.

Estimating radius of influence using a two-dimensional radial flow solution is complicated by the fact that the pore-volume exchange rate varies not only by distance from the extraction well, but also by depth below ground surface. AIR2D model can be used to identify the region in the subsurface that has sufficient pore-volume exchange to achieve remediation goals, as can the equations of Shan, Falta, and Javandel (1992). Peargin and Mohr (1994) have plotted subsurface volumetric flow rates (normalized to the soil gas extraction rate) versus distance from the extraction well (normalized to the vadose zone thickness) based on a numerical two-dimensional radial flow solution. For a given k_h/k_v, the area with a pore-volume exchange exceeding some threshold value is readily identifiable.

An approximate method for determining effective radius of influence, developed by Bass (1993a), involves one-dimensional radial flow in which the volume of gas decreases with distance from the extraction well, reflecting infiltration of air from the ground surface. The surface flux is assumed to be proportional to the subsurface vacuum which drives it, and hence attenuates roughly exponentially with distance from the extraction well. This approach has the simplicity of a one-dimensional radial flow solution but does not overestimate radius of influence by ignoring surface infiltration. Furthermore, effective radius of influence is calculated directly from field data, rather than from intermediate permeability values.

3.2.4.2 Evaluating Effective Radius of Influence Among Extraction Wells

When several vapor extraction wells are placed in close proximity, they are affected by each other's vacuum and flow fields. In the region between the wells, the wells essentially compete for the limited supply of air infiltrating the ground surface, an effect that is exacerbated by high k_h/k_v values and low surface permeability. In the limiting case where the surface is completely sealed, air flow between wells becomes negligible, and all of the air entering the vapor extraction system comes from outside the treatment zone leading to poor remediation performance. Furthermore, the volumetric rate of soil gas extraction is less than would be obtained by simply multiplying the recovery rate for a single well by the number of extraction wells, so air handling and treatment systems may be oversized.

Most analytical one-dimensional and two-dimensional flow solutions offer little insight into this effect since they are inherently single-well solutions. However, the US ACE (1995) outlines how two-dimensional radial flow solutions for several wells can be combined using the principle of superposition to generate potential flow solutions for multiple-well systems. Another approach is to use the calculated permeabilities as input parameters for a three-dimensional numerical model, such as AIR3D — an adaptation of MODFLOW for vapor extraction applications (Joss and Baehr 1995b), to estimate flow fields for multiple-well systems. The model generally must be calibrated so that its predictions conform to measured field parameters. This method provides a rigorous analysis of the phenomenon and can be used to evaluate well spacings in multiple-well systems, the potential need for injection wells, and strategies for operation of nearby wells sequentially or at varying flow rates to move the stagnation point over time.

The approximate one-dimensional method for determining effective radius of influence developed by Bass can be modified to account for the interaction among wells in multiple-well systems (Bass, Lucas, and Kline 1993). The decrease in the volume of gas with distance from each extraction well is modified by the proximity of adjacent extraction wells. The surface flux, which is the source of the air recovered by the extraction wells, is assumed to be proportional to the subsurface vacuum that drives it, but is delivered only to the closest extraction well. This results in a reduced air flow among wells and, therefore, a reduced effective radius of influence and overall gas recovery. This approach has the simplicity of a one-dimensional radial flow solution and provides reasonable predictions of the flow response to an applied vacuum in a multiple-well vapor extraction system. Equations describing this approach are given in Appendix A.

The effective radius of influence is always greater for a single-well system than that of a single well in a system with multiple wells. In a multiple-well system, the single-well radius of influence should be used in determining how far from the edge of the treatment area the wells should be placed, while the multiple-well radius of influence should be used for determining distances between extraction wells. Therefore, ideal placement of vapor extraction wells is slightly bunched in the middle of the treatment area, rather than spread uniformly throughout.

3.2.4.3 Air Injection

When conditions are not favorable for air flow among extraction wells in multiple-well systems due to high k_h/k_v or low k_s/k_a, air injection wells offer a means of introducing air between extraction wells. Injection wells may ultimately speed remediation on the most contaminated areas and allow greater air flow rates than otherwise would be possible. However, such wells entail additional well installation costs and additional energy costs for operating compressors or blowers, and, in some cases, may dilute vapor-phase contaminant concentrations, thereby increasing offgas treatment costs.

Injection wells may be active or passive. Passive inlet wells are open to the atmosphere, allowing air to be drawn into the soil from the lower atmosphere. These wells are typically used to limit the radius of influence of a particular well. An example would be the case where two adjacent properties have volatile contaminants in the subsurface. A passive inlet system installed along the property boundary would allow vapor extraction/ bioventing to proceed at one of the properties without inducing migration of contaminants from the other property (the inlet wells would probably need to be quite closely spaced to create an effective boundary).

When passive injection wells are used to affect air flow paths within a remediation system, there usually must be many more passive wells than extraction wells. This is because they are usually of similar construction to the extraction wells, but the driving force for air movement is lower (subsurface vacuum will have dissipated from the extraction wells to the passive injection wells, often by more than 90%). This effect is mitigated somewhat by the lower upwelling (hence more exposed screen) associated with lower vacuum and the higher well efficiency associated with lower flows in the injection well. Still, unless the subsurface vacuum in the vicinity of the passive injection well is on the order of 10% or more of the applied vacuum, air will be passively injected at only a small fraction of the extraction rate. When venting is relatively shallow (≤3 m [≤10 ft]), an alternative to passive injection wells is a gravel-filled trench, which has a much greater contact area with the soil than a passive injection well, and thus is capable of providing much more air even at low subsurface vacuum levels.

Active injection wells use forced air from a blower or compressor to promote the movement of air through the soil. Active injection is typically used to increase pressure gradients and thus induce higher flow rates in stagnant areas near the fringe of a well's radius of influence. Injection wells should be placed so that contamination is directed toward the extraction wells. Although screened intervals vary in length, they should allow for uniform airflow from the injection to the extraction wells. Injection wells are usually installed vertically outside the edge of the contaminated area. A well-designed soil venting system allows vents to act interchangeably as extraction, injection, and/or passive inlet wells.

The effects of active and passive injection wells can be modeled analytically by superimposing radial flow solutions or numerically using the AIR3D model. Predicting air flow into an injection well is similar to predicting air flow out of an extraction well. However, extraction wells are ordinarily under a substantial vacuum, while injection wells are under pressure or, in the case of passive injection wells, much lower vacuum. The amount of exposed screen is generally greater in the injection well than in the extraction well because upwelling reduces the exposed screen to a much greater extent in the extraction well.

3.2.4.4 Horizontal Wells and Vented Trenches

Increasingly, horizontally drilled wells and horizontal wells placed in excavated trenches are used in vapor extraction applications. Horizontal installations generally produce more air flow at lower applied vacuum and influence at a greater distance than vertical wells. Vented trenches are typically used in situations where groundwater is shallow and may provide good areal influence with lower installation cost and less upwelling of groundwater. Horizontally drilled wells, an offshoot of the oil and gas industry, are used especially where access is limited or where excavation of trenches or installation of vertical wells could create a safety hazard. US EPA recently reviewed environmental applications of directional drilling and a partial list is provided in Table 3.2 (US EPA 1997).

Effective operation of horizontal vapor extraction systems requires that air flux from the formation be uniform over the length of the well. However, frictional losses can result in the bulk of the air being extracted at the end of the well closest to the blower.

To obtain an even influx of air along the length of a horizontal vapor extraction well, the percent open area, represented by the slot density or the number and size of perforations, can be increased at greater distance from the blower to compensate for the reduced vacuum due to frictional losses. A computerized design tool has been developed (McPhee, Bass, and Mott-Smith 1997) to predict how such a variation in open area can be determined so as to ensure constant air flux along the length of the well. This design tool describes air flow using the Manning equation for flow through a circular pipe. The formation and slot resistance to air flow is determined from a horizontal or vertical pilot test (vertical pilot test results can be reduced using standard transport equations for buried vertical rods and buried horizontal cables to represent vertical and horizontal wells, respectively [Bass 1993b]). An iterative procedure is employed to converge on the slot density or hydraulic head profile required to achieve uniform flux along the length of the well. Implementation using standard spreadsheet programs (Lotus 1-2-3, Excel, etc.) produces rapid convergence and ensures ease of use.

3.2.4.5 Thermal Enhancement

Soil heating has been demonstrated to improve the mass removal rate of vapor extraction systems for VOCs and SVOCs. This approach may be particularly suited to lower permeability soils where volatile contaminants must be removed. Raising the temperature of the subsurface increases the rates of removal and transport mechanisms that typically control the rate at which a site can be cleaned up using vapor extraction technology. The mechanisms that are enhanced by heat include:

Table 3.2
Select Vendors of Horizontal Wells and Directional Drilling Technology[a]

Name of Vendor	Address	Contact/Phone
American Augers, Inc. (Drill Rig Manufacturer)	P.O. Box 814 West Salem, OH 44287	Gary Stewart 1-800-324-4930
Davis Horizontal Drilling, Inc.	7204 Timberlake Mustang, OK 73064	Roland Davis (405) 376-2702
Directed Technologies Drilling, Inc.	1315 South Central Avenue, Suite G Kent, WA 98032	Michael Lubrecht 1-800-239-5950
Directional Drilling, Inc.	P.O. Box 159 Oakwood, GA 30566	Jim McEntire (770) 534-0083
Ditch Witch, Inc., The Charles Machine Works, Inc. (Drill Rig Manufacturer)	P.O. Box 66 Perry, OK 73077	Roger Layne 1-800-654-6481
Drilex Inc.	15151 Sommermeyer Houston, TX 77041	David Bardsley (713) 957-5470
Fishburn Environmental Drilling	P.O. Box 278 Marengo, OH 43334	Stuart Brown
GTS Horizontal Drilling Co.	1231 B East Main Street, Suite 189 Meriden, CT 06450	Tom Bryant 1-800-239-8079
Horizontal Drilling Technologies	2414 South Hoover Road Wichita, KS 67215	Mark Mesner (316) 942-3031
Horizontal Subsurface Technologies, Inc.	634 West Clarks Landing Road Egg Harbor, NJ 08215	1-800-965-0024
Horizontal Technologies, Inc.	P.O. Box 150820 Cape Coral, FL 33915	Donald Justice
KVA Slantwell Installations/ KVA Analytical Systems	15 Carlson Lane Falmouth, MA 02540	Steve or Pat (508) 540-0561
Mears/HDD, Inc.	4500 North Mission Road Rosebush, MI 48878-0055	Dick Gibbs 1-800-632-7727
Michels Environmental Services	817 West Main Street (main office) Brownville, WI 53006	Tim McGuire (303) 423-5761
OHM Remediation Services Group	5731 West Las Positas Boulevard Pleasanton, CA 94588	Robert Cox (510) 227-1105
Pledger, Inc.	12848 S.E. Suzanne Drive Hobe Sound, FL 33455	Steve McLaughlin (407) 546-4848
SCHEMASOIL® Schumacher Filters America, Inc.	P.O. Box 8040 Asheville, NC 28814	Anne Ogg (704) 252-9000
Stearns Drilling	6974 Hammond S.E. Dutton, MI 49316	Roland Clapp (616) 698-7770
Treachless Technology Center	Department of Civil Engineering P.O. Box 10348 Louisiana Technical University Ruston, LA 71272	
Vermeer Manufacturing (Drill Rig Manufacturer)	P.O. Box 200 Pella, IA 50219	David Whampler (515) 628-3141

[a] This list is not inclusive of all vendors capable of providing horizontal wells and directional drilling technologies.

Source: US EPA 1997

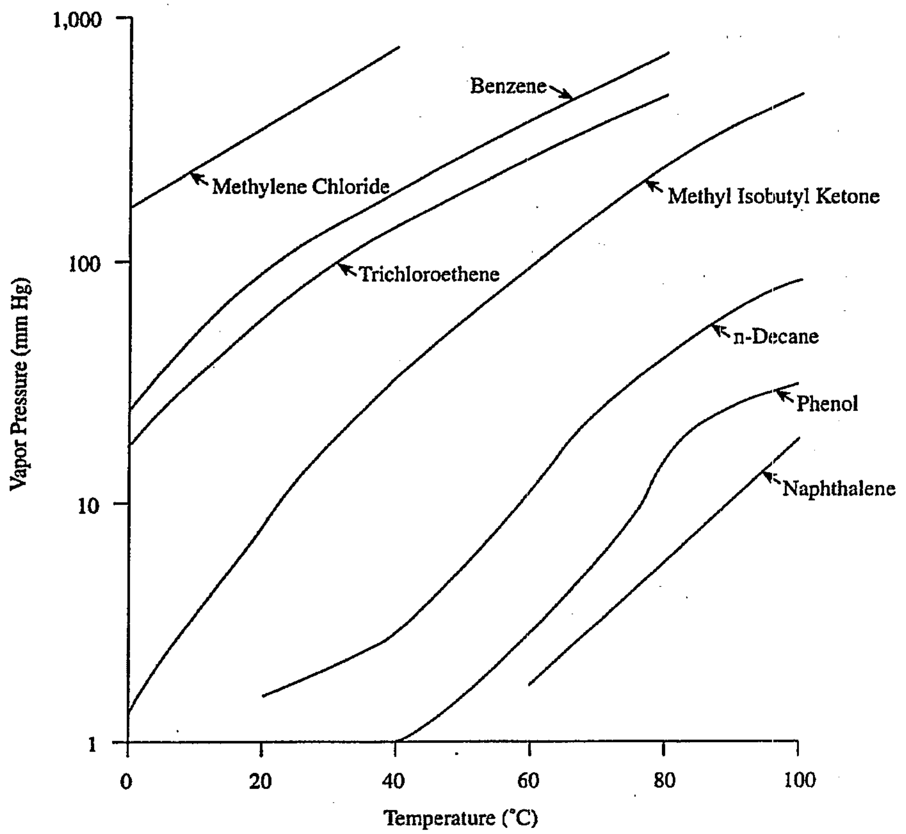
- *Gas Advection* — the movement of air in response to density gradients;
- *Chemical Partitioning to the Vapor-Phase* — the vapor pressure of VOCs and SVOCs is increased significantly with increasing temperature as Figure 3.7 illustrates;
- *Chemical Partitioning to the Water Phase* — the solubilities of most VOCs and SVOCs are not dramatically affected by temperature, but some increase or decrease substantially with increasing temperatures;
- *Gas-Phase Contaminant Diffusion* — contaminant molecules diffuse at a faster rate at higher temperatures;
- *Chemical or Biological Transformations* — while chemical reactions increase with temperature, biological degradation rates increase above ambient temperatures but fall off again at high temperatures; and
- *Soil Drying* — the relative permeability to soil vapors increases as the soil dries.

In a review article, US EPA (1997) described and evaluated five methods of soil heating in conjunction with vapor extraction. The following approaches to thermal enhancement of vapor extraction were evaluated:

- steam injection/stripping,
- hot air injection,
- radio frequency heating,
- electrical resistance heating, and
- thermal conduction heating.

While each of these thermal enhancements has been demonstrated to some extent, they all remain seldom-used niche technologies. The performance and costs associated with each approach were presented along with the limitations specific to each. In addition, case histories were presented for steam injection and electrical resistance heating as well as a list of vendors for each approach. The US EPA study concluded that thermal enhancement technologies can improve mass removal rates and decrease treatment times if certain site or contaminant characteristics constrain standard vapor extraction efficiency. Further details on these techniques follow.

Figure 3.7
Relationship Between Increasing Temperature and Vapor Pressure for Several Chemicals



Adapted from Perry, Chilton, and Kirkpatrick 1963

Steam Injection/Stripping. Steam injection/stripping is an offshoot of enhanced oil recovery technology and consists of injecting steam into the contaminated soil mass in situ. This approach provides both heat and a significant pressure differential in a formation to mobilize contaminants in the vapor, aqueous, and NAPL phases. The heat increases chemical partitioning into the vapor and water phases as contaminants are pushed ahead of the condensing water vapor toward vapor extraction wells.

A steam-generating boiler, controls, fittings, valves, etc. for control of the steam injection are required. Special attention must be paid to the high temperatures anticipated in injection and extraction wells when specifying materials for piping, valves, check valves, and recovery pumps. Steam injection wells are typically constructed of steel.

This approach is most suited to sites with moderate-to-high hydraulic conductivities to allow the movement of the steam through the soil. In addition, the capture, control, and recovery of the condensate plume formed, which can be difficult to predict in low-permeability formations, is crucial to the effectiveness of the method. Therefore, this approach is not recommended for sites with high clay or silt content. However, given proper site conditions, the approach is more applicable to sites where NAPL is present due to the condensate front that moves ahead of the steam and can displace and mobilize NAPL.

Hot Air Injection. Hot air injection can be used to increase the mass extraction flow rate by increasing the soil temperature through injection wells or injection through a large mixing auger. This process can be less expensive than using steam, especially if an inexpensive source of hot air, such as a thermal oxidizer, is available immediately adjacent to the injection wells. However, the process is much less efficient than steam, and costs for insulating hot air piping are significant due to the relatively low heat capacity of air.

This process tends to dry the soil more than steam injection and can improve mass removal from lower permeability soils. Drying lower permeability soils can significantly increase the hydraulic and pneumatic permeability and facilitate higher mass removal rates of volatile organic compounds. However, drying does remove water from the soil, which will ultimately hinder biodegradation, and drying may not be effective on SVOCs.

In addition, if exhaust from a thermal oxidizer or other combustion source is used for the hot air, the oxygen concentration may be much lower than heated ambient air. Furthermore, the output of a thermal oxidizer has significant moisture content as a combustion product and therefore will not dry the soil. If biological degradation is to be enhanced at the site or if drying of the soil is desirable, an air-to-air heat exchanger may be needed to heat ambient air without contacting the oxygen-depleted combustion exhaust.

Radio Frequency Heating. Radio frequency (RF) soil heating uses electrodes or antennae powered by a radio-frequency generator that operates in the industrial, medical, and scientific band (1 to 10 megahertz). The electrodes are either placed on the surface or in boreholes drilled into the contaminated area. Vapor extraction is used to collect the resulting vapors.

RF heating can be used to increase soil temperatures above those attainable by steam injection or hot air injection. During treatment, RF heating dries the soil, which results in decreased thermal conductivity. This has caused uneven and slow heating at some sites (US EPA 1997). At the same time, the pneumatic conductivity is increased by the removal of water in soil pores. Therefore, the net effect is to increase the mass removal rate in the vicinity of the electrodes, and if the electrodes are properly spaced, the contaminated soil mass can be treated.

If this approach is used, selection of construction materials for the wells and the vapor extraction system must account for the highest temperatures anticipated in the soil, typically 150 to 200°C (302 to 392°F)(US EPA 1997). Performance data for four sites where RF heating was used to enhance a vapor extraction system are presented in Table 3.3 (US EPA 1997).

Electrical Resistance Heating. Electrical resistance (ER) heating is comparable to RF heating except it is slightly less efficient in heating the soil. Typically, an array of metal pipes is inserted vertically into the contaminated soil area. By applying an electrical current, a voltage differential is created between electrodes placed in two different boreholes, which causes resistance heating to occur between them. As in RF heating, the soil is dried and VOCs are removed via a vapor extraction system. The same limitations of uneven soil heating and slow heating that occur in RF heating are exaggerated with ER heating because the electrical conductivity of soil decreases dramatically when moisture is removed. For this reason, the attainable temperature using ER heating cannot practically exceed 100°C (212°F), but temperatures high enough to oxidize residual VOCs that are not removed by standard vapor extraction can still be created.

ER heating was applied on a pilot scale at the Savannah River Site in Aiken, South Carolina, to assess the technique's effectiveness in removing VOCs from a 3 m (10 ft) thick clay layer at a depth of approximately 12 m (40 ft) below ground surface in the vadose zone (US EPA 1997). A high-voltage power source (750 kva) was used to supply 480-volt three-phase power to a six-phase power transformer that in turn was connected to a series

Table 3.3
Thermal Enhancement Performance Data

Vendor	Thermal Enhancement	Scale	Date of Demonstration	Location
Battelle Pacific Northwest Laboratories	Six-Phase Soil Heating	Field Demonstration	NA	Aiken, SC
Geo-Con, Inc.	Hot Air Injection	Full	NA	Piketon, OH
Flour-Daniel GTI (FD GTI)	Steam Sparging	Full	1995	Bremerton, WA
FD GTI	Hot Air Sparging	Full	1993	Union, MA
FD GTI	Electrokinetic Heating	Full	1994	Netherlands
Hrubetz Environmental Services, Inc. (Hrubetz)	Hot Air Injection	Full	1990	Ottawa, Ontario Canada
Hrubetz	Hot Air Injection	US EPA Demonstration	NA	Kelly Air Force Base, TX
Hughes Environmental Systems, Inc.	Steam Recovery	Full	1991	Huntington Beach, CA
HT Research Institute	Radio-Frequency Heating	US EPA Demonstration	1994	Kelly Air Force Base, TX
HT Research Institute	Radio-Frequency Heating	Pilot	1992	Rocky Mountain Arsenal, CA
HT Research Institute	Radio-Frequency Heating	Pilot	1989	Volk Air National Guard Base, WI
KAI Technologies, Inc.	Radio-Frequency Heating	US EPA Demonstration	1994	Kelly Air Force Base, TX
Lawrence Livermore National Laboratory	Steam Stripping and Electrical Heating	Full	1993	Lawrence Livermore National Laboratory
Novaterra, Inc.	Steam Stripping	Full	1988	San Pedro, CA
Praxis Environmental Technologies, Inc.	Steam Extraction	Pilot	1988	McClellan Air Force Base, CA
R.E. Wright Environmental, Inc.	Steam Stripping	Pilot	NA	Bradford, PA
SIVE Services	Steam Injection	Full	1989	San Jose, CA

gw	Groundwater	NA	Not applicable	PCE	Tetrachloroethene
TCE	Trichloroethene	ND	Non-detect	TPH	Total petroleum hydrocarbons
DCE	Dichloroethene	DCA	Dichloroethance	BTEX	Benzene, toluene, ethylene, and total xylenes

Source: US EPA 1997

Table 3.3 (cont.)
Thermal Enhancement Performance Data

Target Contaminant	Concentration Before Treatment	Concentration After Treatment	Volume Treated	SoilType	Treatment Time
PCE TCE	ND to 500 mg/kg ND to 200 mg/kg	ND to 0.5 mg/kg ND to 0.5 mg/kg	1,100 yd^3	Clayey Soil	18 days
TCE	1 to 100 mg/kg	10 mg/kg	20,000 yd^3	Clayey Soil	NA
No. 6 Fuel Oil Diesel Fuel	88,000 mg/kg TPH	Ongoing	25,000 yd^3	Sandy Till	Ongoing
Chlorinated Solvents	100 mg/kg soil 10 mg/L (gw)	Ongoing	30,000 yd^3	Glacial Till	Ongoing
BTEX Diesel Fuel	BTEX (gw): 13,400 μg/L Diesel (gw): 7,300 μg/L TPH (soil): 9,000 mg/L	BTEX (gw): ND Diesel (gw): < 50 μg/L TPH (soil): 9 to 220 mg/L	10,500 yd^3	Sandy Clay	24 weeks
Jet Fuel	21,000 mg/L	ND to 215 mg/L	300 yd^3	NA	90 days
Jet Fuel (JP-4)	NA	12,799 lb removed	890 yd^3	NA	18 days
TPH (diesel fuel)	3,790 mg/kg	2,290 mg/kg	150,000 yd^3	Layered Sand/Clay	730 days
Aromatics Nonaromatics	40 mg/kg 200 mg/kg	2.84 mg/kg 7.2 mg/kg	44 yd^3	Silt, Clay, and Cobbles	60 days
Aldrin Dieldrin Endrin Isodrin	1,100 mg/kg 490 mg/kg 630 mg/kg 2,000 mg/kg	11 mg/kg 3.2 mg/kg 2.8 mg/kg 2.8 mg/kg	30 yd^3	Sandy Clays and Clayey Sands	35 days
Aromatic VOCs Aliphatic VOCs Aromatic SVOCs Aliphatic SVOCs Hexadecane	212 mg/kg 4,189 mg/kg 252 mg/kg 1,663 mg/kg 31.5 mg/kg	0.88 mg/kg 28 mg/kg 2.3 mg/kg 95 mg/kg 5.4 mg/kg	19 yd^3	Sandy Soil	13 days
Total Recoverable Petroleum Hydrocarbons	1,238 mg/kg	636.9 mg/kg	56 yd^3	Sandy Soil	45 days
BTEX TPH (gasoline)	4,800 mg/kg 8,600 gal	140 mg/kg 1,000 gal	100,000 yd^3	Alluvial Soil with Silt Clay and Gravel	145 days
DCA DCE Bis(2-ethylhexyl)phthalate Aromatics Butyl Carbitol	10 to 200 mg/kg 20 to 100 mg/kg 100 to 80,000 mg/kg 1,200 mg/kg 6,000 mg/kg	0.47 to 0.82 mg/kg 0.23 to 2.41 mg/kg 52.67 mg/kg 10.77 mg/kg 4.20 mg/kg	30,000 yd^3	NA	Late 1989 to Early 1990
TCE	ND to 40 mg/L	ND to 0.05 mg/L	5,000 yd^3	NA	NA
TPH	50,000 to 100,000 mg/kg	4,500 mg/kg	330 yd^3	NA	45 days
VOCs	NA	70,000 lb removed	30,000 yd^3	NA	400 days

of electrodes placed in boreholes in a 9 m (30 ft) wide hexagonal pattern within the impacted area. Vapors, including steam, were captured, condensed, and treated by electrical catalytic oxidation.

The results indicated the range of removal of TCE and PCE from soil to be 93 to 99.7%. The mass removal rate of PCE increased threefold after the treatment zone was heated and dried. Approximately 17,000 L (4,486 gal) of water were removed as steam from the pilot test site due to drying of the soil.

Thermal Conduction Heating. Thermal conduction heating uses electrical heating elements placed on the surface of the soil or in boreholes to heat and volatilize VOCs in the soil above the water table. This method is slow and inefficient in comparison to the other soil heating methods, but it can be less expensive. The approach would be most applicable to sites with shallow contamination, low-permeability soils, and VOCs with low boiling points. Clearly, if a heating element is placed in a potentially explosive atmosphere, the element must be explosion-proof, and the atmosphere above the soil must be monitored to ensure safe working conditions. Little documentation of applications of this technique are currently available.

3.2.4.6 Pneumatic and Hydraulic Soil Fracturing for Clay Soils

Pneumatic and hydraulic fracturing of fine-grained and consolidated sediments is an offshoot of the oil field production industry where it has been used successfully to enhance the production of oil extraction or injection wells. This technique involves the injection of air or liquids (water or slurries) into a formation to create fractures and increase the permeability of the area surrounding a recovery well. When applied to vapor extraction, this technique can improve the pneumatic and hydraulic conductivity of sites where residual VOCs are present in tight clay or silt soils. In some cases, it may make vapor extraction possible where it otherwise would be ruled out.

Compressed air injection requires a sudden, massive volume of air which is normally supplied by gas cylinders. The gas cylinders are charged by compressors and can deliver 800 to 1,800 ft^3/min at pressures of 500 to 2,000 kPa (approx. 70 to 300 psi). Pneumatic fracturing also requires the use of open boreholes which later can be completed as extraction wells. Pneumatic fracturing is a developing technology for enhancing vapor extraction and, as such, limited performance or cost information is available. Table 3.4 summarizes the results obtained to date at several sites where pneumatic fracturing has been applied.

Table 3.4
Select Examples of Remediation Technologies Enhanced by Pneumatic and Hydraulic Fracturing

Technology	Developer or Vendor	Site Location	Geologic Formation Type	Wastes Treated	Technology Performance After Fracturing
Pneumatic Fracturing and SVE with Hot Gas Injection	Accutech Remedial Systems, Inc.	Somerville, NJ	Shale	VOCs, primarily TCE	• Rate of air flow increased by more than 600%. • Rate of TCE mass removal increased by approximately 675%.
Pneumatic Fracturing and SVE	Accutech Remedial Systems, Inc.	Santa Clara, CA	Silty clay, sandy silts, and clays	VOCs, primarily TCE	• Rate of air flow increased 3.5 times. Permeability increased as much as 510 times. • Rate of TCE mass removal in clay zones increased as much as 46,000 times.
Pneumatic Fracturing and DVE	Accutech Remedial Systems, Inc.	Highland Park, NJ	Shale	VOCs, primarily TCE	• TCE mass removal increased times.
Pneumatic Fractuing and Fuel Recovery	Accutech Remedial Systems, Inc.	Oklahoma City, OK	Shale and sandstone	No. 2 Fuel Oil as free product	• Rate of recovery of free product increased by approximately 1,600%.
Pneumatic Fracturing and In Situ Bioremediation	Accutech Remedial Systems, Inc.	Oklahoma City, OK	Sandy, silty shale, and clay stone	VOCs, primarily BTEX and TCE	• Transmissivity increased by approximately 400%.
Pneumatic Fracturing and In Situ Bioremediation	Accutech Remedial Systems, Inc.	Flemington, NJ	Shale	VOCs, primarily TCE	• Transmissivity increased by 85%.
Pneumatic Fracturing and SVE	Accutech Remedial Systems, Inc.	Coffeyville, KS	Silty clay	VOCs, primarily TCE	• Rate of air flow increased more than 5 times.
Pneumatic Fracturing and DVE	Terra Vac, Inc.	New York, NY	Clay soils	TCE, PCE, BTEX, and other VOCs	• Rate of air flow did not increase appreciably. • Concentration of VOCs in the extracted air stream increased 10 times.

Table 3.4 cont.
Select Examples of Remediation Technologies Enhanced by Pneumatic and Hydraulic Fracturing

Technology	Developer or Vendor	Site Location	Geologic Formation Type	Wastes Treated	Technology Performance After Fracturing
Pneumatic Fracturing and DVE	Terra Vac, Inc.	Monroe, LA	Clay soils	TCE, PCE, BTEX, and other VOCs	• Rate of air flow increased by 6 to 8 scfm. • Rate of extraction of VOCs more than doubled.
Pneumatic Fracturing and In Situ Bioremediation	New Jersey Institute of Technology	Marcus Hook, PA	Clay soils	BTEX	• Soil permeability increased 40 times. • Rate of removal of BTEX increased by more than 82%.
Pneumatic Fracturing and SVE	New Jersey Institute of Technology	Richmond, VA	Clay	VOCs, primarily methyl chloride and TCA	• Rate of air flow increased 1,000 times. • Concentration of VOCs in the extracted air stream increased 200 times.
Pneumatic Fracturing and DVE	First Environment, Inc.	Greenville, SC	Biotite gneiss and schist	Chlorinated solvents	• Recovery rate increased as much as 10 times.
Hydraulic Fracturing and SVE	University of Cincinnati	Oak Brook, IL	Silty clay	TCE, TCA, DCA, and PCE	• Average rate of extraction increased 15 to 20 times. • Concentration of contaminants recovered increased 10 times.
Hydraulic Fracturing and In Situ Bioremediation	University of Cincinnati	Dayton, OH	Sandy and silty clay	BTEX and TPH	• Rate of fluid flow increased 25 to 40 times. • Level of contaminant reduction was 89% greater for BTEX and 77% greater for TPH.

Hydraulic Fracturing and SVE	University of Cincinnati	Beaumont, TX	Clay	Gasoline and cyclohexane	• Rate of recovery of LNAPL increased 10 times.
Hydraulic Fracturing and SVE	Fuss and O'Neill, Inc. and FRX Inc.	Woodstock, CT	Silty clay	VOCs, primarily paint thinner	• Rate of fluid flow increased as much as 6 times.
Hydraulic Fracturing and In Situ Bioremediation	FRX Inc.	Denver, CO	Shale and clay	TPH	• Reduction of concentrations of TPH in soils was approximately 90% in 5 months.
Hydraulic Fracturing and SVE	FRX Inc.	Lima, OH	Clay and silty clay	Gasoline	• Rate of fluid flow increased more than 10 times.
Hydraulic Fracturing and SVE	FRX Inc.	Oakfield, ME	Clay and silty clay	Gasoline and diesel fuel	• Rate of fluid flow increased as much as 10 times.
Hydraulic Fracturing and Electroosmosis	FRX Inc.	Columbus, OH	Clay and silty clay	Unspecified water-soluble contaminants	• Graphite-filled fractures created an electrical field required to induce electroosmotic migration of water and contaminants.
Hydraulic Fracturing and DVE	Golder Applied Technologies, Inc.	Atlanta, GA	Clay	Chlorinated solvents	• Average product recovery rate increased 4 times.
Hydraulic Fracturing and DVE	Frac Rite Environmental, Ltd. and Echo-Scan Corporation	Alberta, Canada	Clayey silt, silty sands	Hydrocarbon condensate and free-phase hydrocarbons	• Hydraulic conductivity increased 10 times and the ROI increased 4 times. • Volumetric rate of recovery of condensate increased approximately 7 times.
Hydraulic Fracturing and SVE	Remediation Technologies, Inc.	Bristol, TN	Bedrock	TCE	• Rate of extraction increased by as much as 6 times. • Rate of TCE extraction increased by as much 70 L/min.

Source: US EPA 1997

Hydraulic fracturing consists of injecting water or a slurry into a borehole to create and maintain fractures for air and water movement. The slurry may consist of sand, guar gum gel, or other materials that can prop open the fracture after it is formed (US EPA 1997). The borehole is constructed with a hollow-stem auger fitted with a fracturing lance designed especially for this purpose and is terminated just above the target zone. The fracturing lance creates a space below the auger casing within which high-pressure water is injected to form the fracture. Once the fractures are created, a sand slurry can be injected to create secondary permeability from fissures that form preferential migration channels.

Fracturing is not recommended for sites where buildings are nearby. The fracturing pressure must be carefully calculated and controlled to induce fractures useful to vapor extraction. Therefore, detailed borehole logs that are representative of the soil column are critical in planning for, and successfully executing, a fracturing project. Table 3.4 lists the results obtained at sites where hydraulic fracturing has been applied to date, and Table 3.5 lists vendors of this technology (US EPA 1997).

3.2.4.7 Dual-Phase Vapor Extraction

Modifications to a dual-phase vapor extraction system that can increase the mass removal rate include drop-tube entrainment, well screen entrainment, and down hole pumping.

Drop-Tube Adjustments and Air Bleed Valves. The simplest form of dual-phase vapor extraction consists of a vertical well screened across the water table with a drop tube for collection of fluids (Figures 3.8 and 3.9). Practical experience has shown that entrainment of water in the drop tube can be sporadic and has been described as a slurping sound, similar to that created by sucking a cold drink though a straw at the bottom of a glass. In fact, the term "slurping" has been coined to indicate the process of collecting liquid and air at the water table interface through a drop tube (US ACE 1995). When NAPL is also collected and the intent is to also provide oxygen for biodegradation, the term *bioslurping* is applied.

The most common modification to dual-phase systems is adjustment in the depth of the drop tube. Assuming the applied vacuum and air flow rate is sufficient to entrain liquids and air, the depth of the drop tube will determine the relative amounts of liquid and air removed. Depending upon the soil type, the working water table level within the well will typically reach equilibrium quickly after lowering the drop tube. The working water table can be maintained at the LNAPL/water interface to minimize formation of a smear zone, which is typically formed by conventional water table depression and LNAPL collection systems.

Table 3.5
Select Vendors of Pneumatic and Hydraulic Fracturing Technology[a]

Name of Vendor	Address	Contact/Phone
	Pneumatic Fracturers	
Accutech Remedial Systems, Inc.	Cass Street and Highway 35 Keyport, NJ 07735	John Liskowitz (908) 739-6444
First Environmental, Inc.	90 Riverdale Road Riverdale, NJ 07457	Richard Dorrler (201) 616-9700
McLaren/Hart Environmental Engineers, Inc.	25 Independence Boulevard Warren, NJ 07059	James Mack (908) 647-8111
Terra Vac, Inc.	92 North Main Street Windsor, NJ 08561	Loren Martin (609) 371-0070
	Hydraulic Fracturers	
EMCON	3300 North San Fernando Boulevard Burbank, CA 91504	Donald L. Marcus (818) 841-1160
ERM-Southwest, Inc.	16300 Katy Freeway, Suite 300 Houston, TX 77094-1609	H. Reiffert Hedgcoxe (713) 579-8999
Frac Right Environmental, Ltd.	6 Stanley Place S.W. Calgary, Alberta Canada T2S 1B2	Gordon H. Bures (403) 620-5533
FRX Inc.	P.O. Box 37945 Cincinnati, OH 45222	William W. Slack, Ph.D. (513) 556-2526
Fuss and O'Neill, Inc.	146 Hartford Road Manchester, CT 06040	David L. Bramley (203) 646-2469
Golder Applied Technologies. Inc.	3730 Chamblee Tucker Road Atlanta, GA 30340	Grant Hocking (770) 496-1893
Gregg Drilling and Testing, Inc.	2475 Cerritos Avenue Signal Hill, CA 90806	John Gregg (310) 427-6899
Remediation Technologies, Inc.	23 Old Town Square, Suite 250 Fort Collins, CO 80524	Ann Colpitts (970) 493-3700

[a] This list is not inclusive of all vendors capable of providing pneumatic and hydraulic fracturing technologies.

Source: US EPA 1997

Figure 3.8
Schematic of a Dual-Phase Extraction System

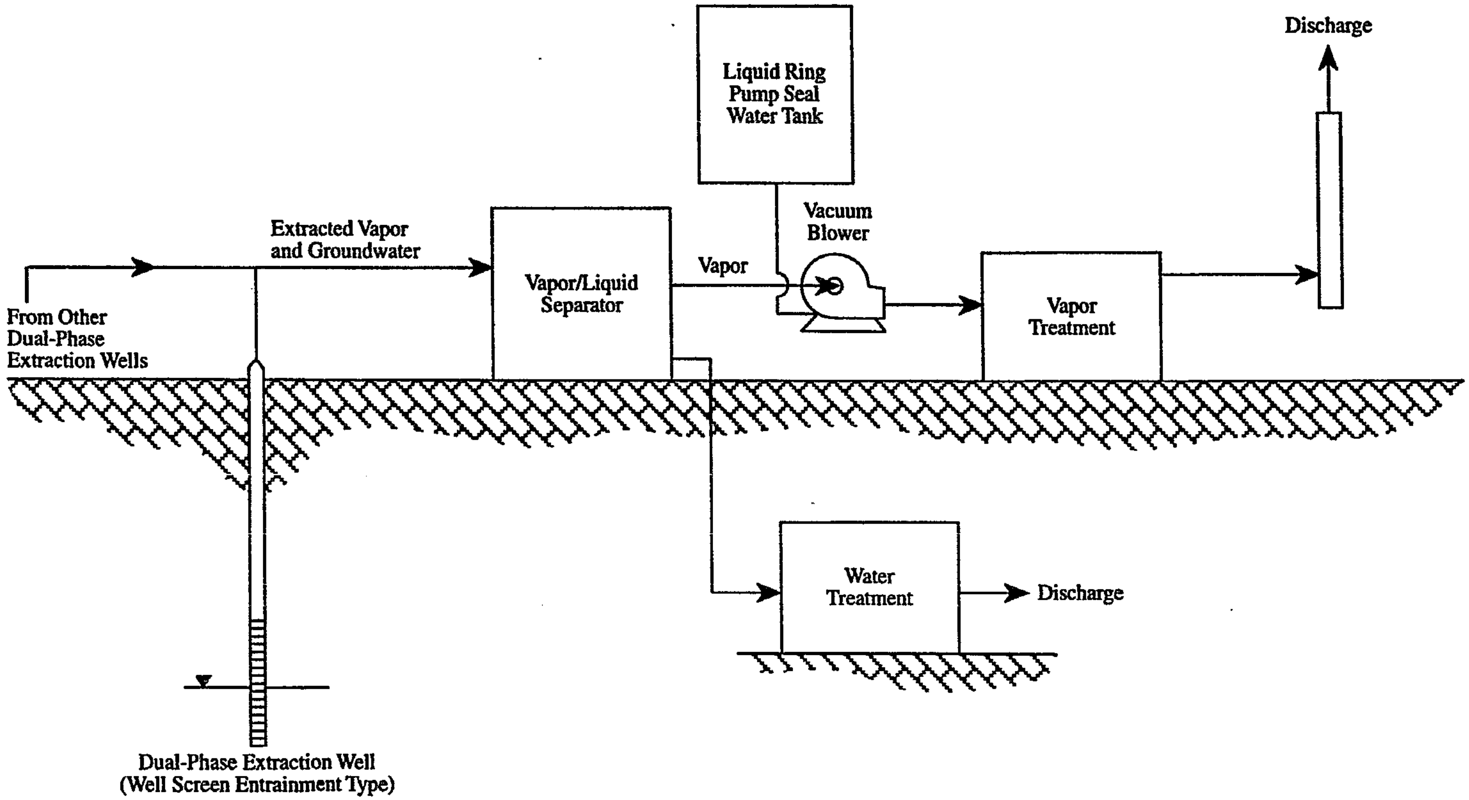
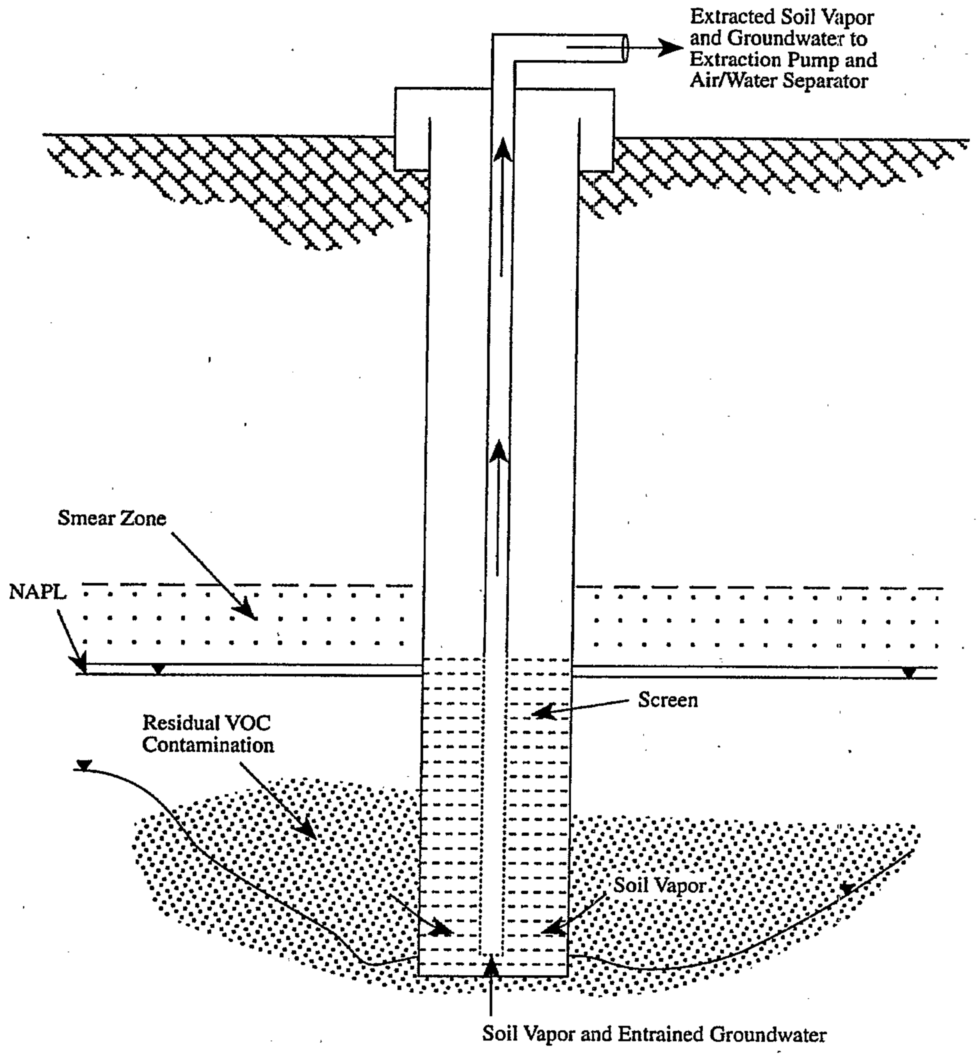


Figure 3.9
Dual-Phase Drop-Tube Entrainment Extraction Well



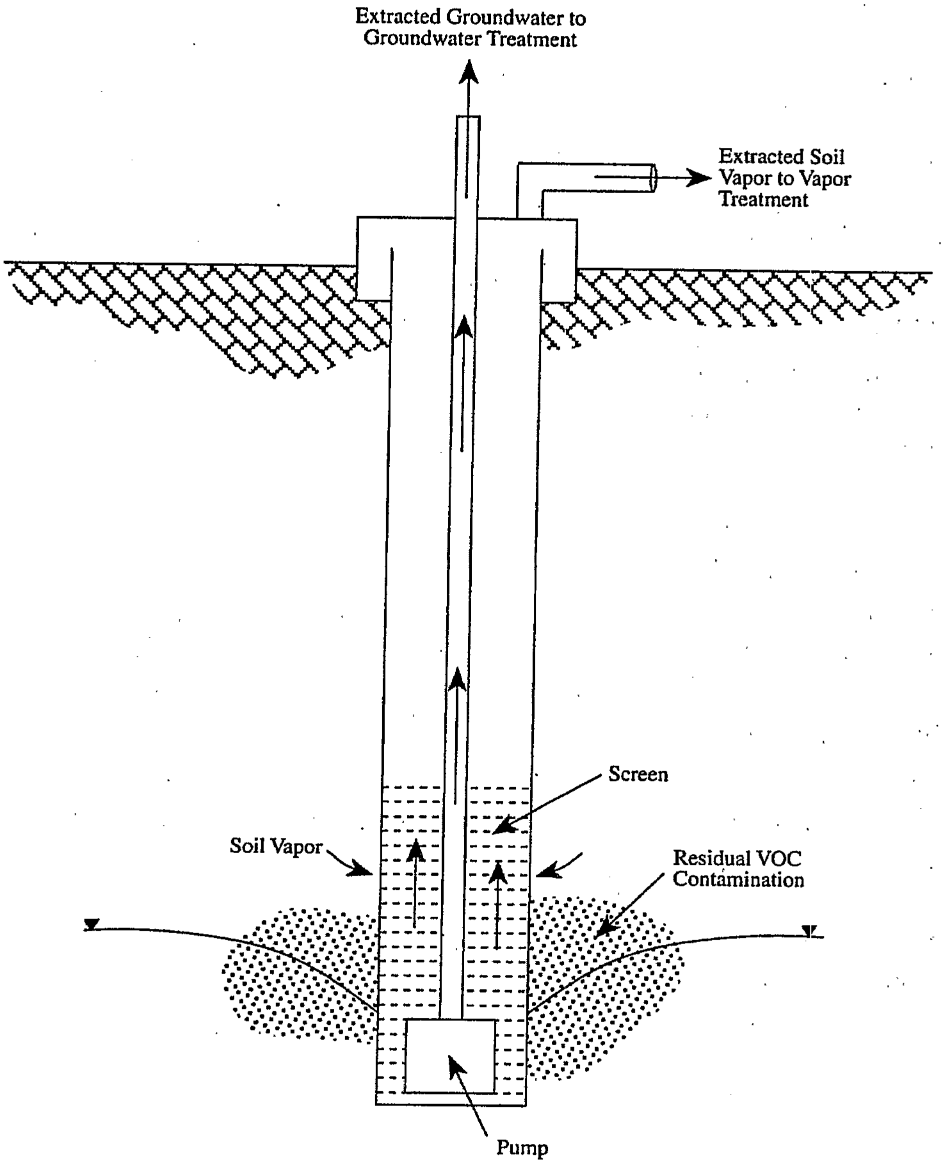
In soil with high hydraulic conductivities, it may be necessary to use a bleed air line to introduce air at the bottom of the drop tube to initiate air and liquid flow up the tube. This approach consists of a small-diameter tube, typically 1.25 cm (1/2 in.) diameter or less, installed along the side of the drop tube. One end extends to the bottom of the drop tube and the other exits the top of the wellhead through a sealed opening and is connected to a valve to the atmosphere. If the bottom end of the drop tube is submerged and no water is forthcoming with the applied vacuum, the air bleed valve at the top of the wellhead can be opened, allowing a small amount of air to enter the well at the bottom of the drop tube. Another method of initiating air and liquid flow is to raise the drop tube and lower it slowly until flow is initiated. In some cases, compressed air may be needed to feed the air bleed valve. This creates an air lift effect and will result in rapid withdrawal of liquids and lowering of the working water level to the bottom of the drop tube. After dual-phase flow is initiated and the working water level is near the bottom of the drop tube, the bleed air valve can usually be closed.

Well Screen Entrainment. In applications of dual-phase extraction to shallow soils (less than 7.5 m [25 ft]), drop tubes may not be necessary to achieve collection of liquids and vapors (US EPA 1997). If smaller diameter wells are used (5 cm [2 in.] or less) and the air flow rate and vacuum is sufficient, liquids can be effectively entrained into the air stream for collection and treatment at the ground surface. This results in a less expensive system and may allow the use of existing monitoring wells as extraction wells. However, the approach provides less flexibility and control over air and water recovery rates than the other methods in this section and so is not a particularly robust design. Certainly, this approach is not applicable to deeper wells.

To effectively dewater dual-phase extraction wells without drop tubes, it may be necessary to install an air bleed tube in the well as described in Section 3.2.4.7. In this case, the air bleed tube is simply a small-diameter polyethylene tube (1.25 cm [1/2 in.]) with a weight on the end to ensure one end sinks to the bottom of the well bore. The other end extends to the wellhead through a sealed hole and into a control valve that can allow entry of ambient air. To prevent accumulated solids at the bottom of the well bore from clogging the tube, the tube can be tied onto the top of a piece of steel pipe, approximately 30 to 60 cm (1 to 2 ft) long, which is capped at the bottom end and lowered to the bottom of the well bore.

Downhole-Pump Extraction. This modification adds a submersible pump to the typical vapor extraction well as shown in Figure 3.10. The submersible pump operates to maintain the water level in the well at a predetermined depth. This depth normally exposes a smear zone to air flow due to the vacuum applied to the well casing.

Figure 3.10
Downhole-Pump Extraction Well



This technique is especially useful at depths exceeding 7.5 m (25 ft), where the yield of a well exceeds 56.78 L/min (15 gal/min), or where a smear zone must be exposed to circulating air. As with conventional extraction wells, the submersible pump must have a separate discharge line and be placed and controlled such that it will turn off when the water in the well reaches the working level. The pumping rate and vacuum applied to the extraction well are adjusted to maximize mass removal in both the liquid- and vapor-phase. Variable-speed pumps can be used to match the water yield of the well. Downhole pumping systems do not result in the rapid mixing of air and water typical of other dual-phase extraction systems and they may produce much greater quantities of water than drop-tube systems, but for high-permeability soils, such systems may be the only way to expose contaminated soils to vapor extraction air movement.

3.3 Equipment Selection

This section addresses the design of vapor extraction and bioventing wells and piping. In addition, guidance is provided for selection of the major pieces of equipment necessary for a successful vapor extraction, dual-phase, or bioventing project. Refer to Sections 3.9.3 for specifications for wells and piping systems and to Sections 3.3.1 and 3.5 for information on pre- and posttreatment equipment, respectively.

3.3.1 Pretreatment Equipment Selection

There is relatively little pretreatment equipment required for vapor extraction/bioventing applications. Required equipment usually includes air/water separators and particulate filters, each of which is discussed in this section.

3.3.1.1 Air/Water Separators

Extraction of soil vapor includes both the unintentional and intentional removal of soil moisture. The soil moisture needs to be removed from the offgas to (1) protect the blower and (2) facilitate treatment for both vapor- and dissolved-phase contaminants. Regenerative and positive displacement blowers are sensitive to water going through them since water will result in internal corrosion and affect the seals.

While liquid-ring blowers require water to form a seal, air/water separation is still required after the blower to treat each medium. In addition, water recovered from the subsurface may not be suitable for seal formation in a liquid-ring blower so air/water separation may be required before the blower in this case.

For many applications, soil moisture is removed unintentionally through offgas condensation and entrainment of soil moisture. The relative humidity of soil gas is typically 100%, at least initially in the project. In addition, the soil gas temperature remains relatively constant if it is being extracted at least 1.5 m (5 ft) below the ground surface. When the soil gas enters pipes above ground or near the surface below ground, the temperature may be colder, and in these cases, moisture condenses from the soil gas. Such condensation can be particularly heavy in winter conditions. The amount of condensation can be estimated through the use of psychometric charts. Typically, a vapor extraction system may generate as much as tens of gallons per day of moisture through condensation depending on the initial soil moisture content, rainfall events, total air flow, and temperature changes.

A vapor extraction system may also intentionally or unintentionally entrain water if the vapor extraction wells intersect perched water or the water table. In these instances, the source of the water is not condensation, but rather soil water pulled into the extraction well screen under the influence of the system vacuum. At sites with tight soils and high moisture content, it may be a design objective to apply sufficiently high vacuum that will result in the removal of soil pore water and even the "slurping" of groundwater to aid in the recovery of NAPL and to increase the air-filled pore space of the soil. Whether intentional or unintentional, removing entrained water from soil can produce a substantial volume of water that needs to be removed with an air/water separator.

Almost all air/water separators used on vapor extraction/bioventing applications are centrifugal separators. The air/water enters a tank through a tangential inlet to create a vortex, and the gas stream is expelled through the top of the cylinder. This vortex forces water particles to the outside wall where they settle to the bottom by gravity (US ACE 1995).

Design considerations include:

- *Amount of Storage Volume Required in the Air/Water Separator* — For separators without automatic liquid removal, the tanks should be sized to hold the amount of water accumlated over several weeks to minimize system maintenance requirements.
- *Vessel Vacuum Rating* — The vessels need to be rated at a vacuum commensurate with the applied vacuum. In some cases, vacuum relief valves are installed on the vessels for protection.
- *Heat Tracing* — Many air/water separators are located outside or in unheated areas; heat tracing is required to prevent freezing of the separator water.
- *Water Removal Systems* — Water removal may be as simple as shutting down the system and opening a drain to remove water or as complex as an automatic pumping system that gauges and removes water from the separator. More complex pumping systems are typically used for those applications where removal rates may exceed a hundred gallons per day. When designing automatic pumping systems, engineers need to account for the vacuum in the separators against which the pumps will need to work.
- *High-Level Shutoff* — Almost all air/water separators include high-level alarms that automatically shut off the blower. These protect the blower from pulling water through them.
- *Head Loss Through the Separator.*

3.3.1.2 Particle Removal

Particulate filters are typically installed between the air/water separator and the blower inlet. Although the condensate removal system will decrease the concentrations of airborne particulate, the removal efficiency may not be sufficient. High particulate levels may cause operational problems with the blower, downstream piping, or offgas treatment equipment. Particulate air filters should be employed to remove airborne particles down to the 1 to 10-micron range.

Cartridge filters are often used for this application. Filter elements are manufactured from a wide variety of materials, including pleated paper, felt, or wire mesh. Felt and wire mesh filters may be washed. The filter is selected based on air flow rate, desired removal efficiency, and pressure drop. Pressure gauges or a single differential pressure gauge should be installed upstream and downstream of the filter. Filters should be changed when indicated by the pressure differences across the filter.

3.3.2 Well Construction and Field Piping Layout/Trenching

Section 3.8 provides construction details and specifications for vertical and horizontal vacuum extraction wells, monitoring points, and piping.

3.3.2.1 Well Screen Placement

The main objective in extraction well placement is to induce air to flow through the zone of contamination. Well screen placements range from screening the entire unsaturated zone to screening a short interval corresponding to the thickness of a highly contaminated zone. In general, extraction wells should be screened only within the impacted zone.

If groundwater has been impacted, the greatest concentrations of vapors will often be found immediately above the water table, especially when free-floating product is encountered. In this case, the screened sections of the wells should be placed in proximity to the water table for optimal removal efficiency (but with some portion of the vent screen extending far enough above the water table to prevent upwelling or seasonal variations in water level from occluding the screen). Additionally, the placement of the well screen deeper in the soil column has been shown, both analytically and empirically, to maximize the radius of influence of a given extraction well (Shan, Falta, and Javandel 1992). Flow models, such as AIRFLOW, AIRTEST, or MODFLOW may be used to optimize screen depths.

Passive/active injection wells are similar in construction to extraction wells (e.g., diameters typically 5 to 10 cm [2 to 4 in.]), but they sometimes have longer screened intervals. Injection wells should generally be piped so that they can be used as extraction wells and vice-versa.

Monitoring wells screened in more than one soil stratum may not provide an accurate indication of the specific soil strata where the contamination is present. In most cases, vapor monitoring wells can be simple and inexpensive (e.g., 2.5 cm [1 in.] diameter, driven well points). To accurately represent the VOC concentration in or near the vadose zone impacted area, monitoring wells with short screened intervals are recommended (e.g., less than 60 cm [2 ft]). Nested vapor monitoring wells can be effective only if the annular seal can be proven to be intact.

3.3.2.2 Construction Considerations for Piping Layout

Many site-specific factors need to be considered in designing the location of the remediation system equipment and the layout of the piping network. These factors primarily relate to the activities occurring on the property and the existing structures and features in the vicinity of the area to be remediated. Within these site-specific constraints, the overall objective of the layout is to minimize construction costs.

Specific factors that should be considered while designing the placement of the remediation equipment and piping include:

- location of existing buried and overhead utilities and the electrical power source for the remediation system;
- current plant operations and levels of activity;
- future plant construction plans;
- building lines/right-of-way/zoning requirements;
- proximity to residential areas;
- existing facility structures (buildings, ASTs/USTs, storage yards, etc.);
- aesthetics (e.g., straight paving cuts and patching) ;
- proximity to sewers, if applicable;
- available pipe fittings (e.g., 12.5-, 45- and 90-degree elbows); and
- surface cover in the area to be remediated (e.g., locating piping in grassed areas versus paved areas).

Once these factors have been considered, an optimal equipment location and piping scheme will become apparent.

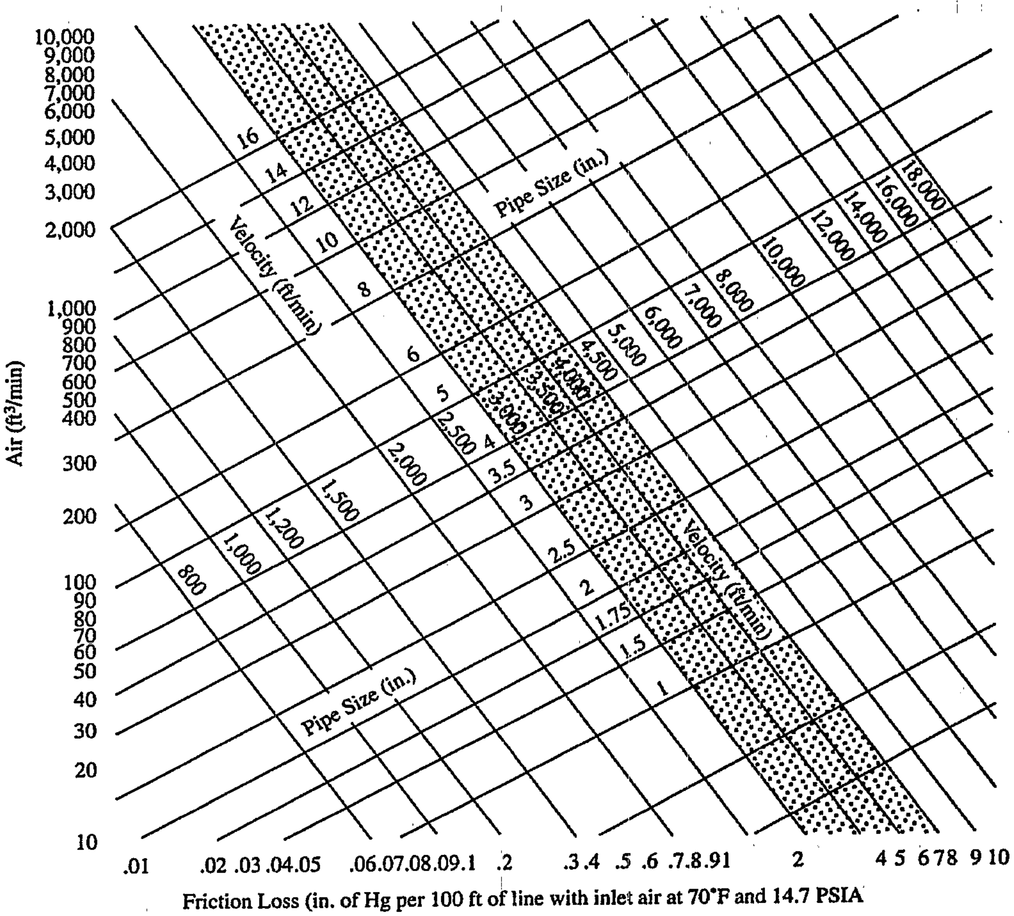
3.3.2.3 Pipe Material Selection and Sizing

Selection of an appropriate piping material is an essential design step. The key considerations include (1) costs, (2) process conditions (e.g., temperature, pressure, freeze/thaw, expected condensate, etc.), (3) compatibility with process chemicals, and (4) environment in which the piping will be placed. For vapor extraction systems, polyvinyl chloride (PVC) is commonly the most economical and effective piping material, except where elevated temperatures are expected, such as near the exhaust port of a vacuum blower.

Once the piping material has been selected and the piping layout has been identified, it is possible to identify the appropriate piping diameter. Of course, to complete the pipe sizing analysis, the design flow rates and temperature/pressure conditions through the piping network must also be established. Pipe sizes are selected by evaluating friction losses for various pipe diameters and selecting a pipe diameter that offers an acceptable head loss. For a system that is to include an individual vapor extraction pipe extending to each extraction well, a conservatively estimated common diameter can be established by investigating the frictional losses that occur in the longest vapor extraction piping run. This simplified approach is as follows:

1. Select the longest piping run (e.g., pipe from furthest extraction well to the remediation equipment);
2. Calculate the total length of the pipe (horizontal and vertical);
3. Estimate the number of valves and fittings and translate these numbers to equivalent pipe lengths using various published tables;
4. Add the equivalent pipe lengths to the total pipe length;
5. If pipe is to process air, convert the design scfm flow rate to acfm under the design operating temperatures and pressures;
6. Given the total pipe length and the design flow rate, determine frictional head loss for several pipe diameters by consulting published friction loss charts (Figure 3.11) or by direct calculation (e.g., using the Darcy-Weisback equation);
7. Compare the magnitude of the calculated friction loss for each pipe diameter to the magnitude of the design vacuum or pressure condition to be exerted on the subsurface; and
8. Select a pipe diameter that results in frictional losses less than 5% of the design vacuum/pressure.

Figure 3.11
Friction Loss Chart
(not to scale)



A chart like this, drawn to scale, can be used to compute friction losses in a piping system. For example, determine the friction loss incurred when 70 ft³/min flows through a 2 in. pipe, 50 ft long.

Step 1: Intersect 70 ft³/min and the sloping line for 2 in. pipe.

Step 2: Drop a vertical from this point of intersection and read the loss, 100 ft of line. If this chart were to scale, the loss would be 60 Hg/100 ft.

Step 3: Multiply the loss/100 ft of line by the length of run/100 ft. The loss for 50 ft, then is:

$$60\left(\frac{\text{length of run}}{100\text{ ft}}\right) = 60\left(\frac{50\text{ ft}}{100\text{ ft}}\right) = 0.30\text{ in. Hg}$$

Also: Velocity in the line may be read from the negatively sloping lines on the graph. To get 70 ft³/min through a 2 in. line, the air must travel at a velocity of approximately 3,000 ft/min.

Reproduced courtesy of Spencer Turbine Company (1987)

This simplified approach is best applied when piping segments to the extraction wells do not vary significantly in length and the velocity does not change significantly between piping segments. If significant variations in pipe length and/or flow rates are expected between piping segments or where manifolding of piping of various diameters is involved, the calculation of friction losses for each individual pipe segment may be necessary.

3.3.3 Blowers (Vacuum Pump) Selection

The blower is a crucial component of a vapor extraction system and its selection, therefore, must be made after carefully considering the system requirements. One of the most basic requirements that a blower must meet is to provide the design system air flow and vacuum while accommodating frictional losses through piping and other equipment components (e.g., air/water separator, filters, offgas treatment system, etc.). Other blower considerations include power use, maintenance requirements, flexibility, noise, and potential as an ignition source. This section identifies a method for determining the blower system design requirements and various types of blowers that have been employed.

3.3.3.1 System Curve Development

A blower may only be properly specified for a system once the system flow and vacuum requirements have been defined. These flow and vacuum requirements are established during the design based on soil permeability, extraction configuration, and frictional losses through system components. The established relationship between applied vacuum and extracted soil vapor air flow, accounting for all frictional losses, is referred to as the *system curve*. A suggested approach to defining these requirements and developing a system curve that has largely been adapted, with permission, from US ACE 1995, is provided in this section.

The first step in developing the system curve is to define the relationship between applied vacuum to the soil and the resulting soil vapor yield. This is commonly determined from a single well during a pilot study by varying the magnitude of the applied vacuum and measuring the corresponding soil vapor yield from the well. The single well vacuum/flow relationship is often directly extrapolated to the number of wells that are to be included in the extraction system to obtain total system flow at various applied vacuums (the *baseline curve*). It should also be noted that the soil vapor yield estimated with this extrapolation is conservative (high) because it does not account for the competing effects of multiple wells. Various models have been used to better predict the soil vapor yield in a multiwell system.

As discussed above, the system curve accounts for all friction losses. Therefore, during the development of the system curve, friction losses in piping and system components are calculated for a range of flow rates. These calculated frictional losses are added to the baseline curve in order to obtain the system curve.

The friction losses in the piping are most readily calculated by looking up unit head losses for various flow rates (in acfm) in published charts as discussed in Section 3.3.2.3. Equipment losses are generally obtained from manufacturers' literature. Components often included in vapor extraction systems for which head loss estimates for various flow rates would need to be determined include:

- particulate filter,
- moisture separator,
- silencer, and
- granular activated carbon.

The engineer must verify that the flow rates and pressures are within the operating range of the blower.

Where there are several geological units on-site with air permeabilities that differ greatly, it may be difficult or inefficient to attempt to balance the flows to a single blower. It may be worthwhile to design multiple blowers, configured in parallel. Each blower would have a blower curve that would match the associated geological unit.

3.3.3.2 Blower Alternatives

The type and size of blower selected for a vapor extraction system should be based on both the vacuum required to achieve the design vacuum at the extraction wellheads (including upstream and downstream piping and equipment losses) and the total design flow rate. Five types of blowers are commonly considered for vapor extraction/bioventing systems: regenerative blowers, rotary-lobe blowers, liquid-ring vacuum pumps, centrifugal exhausters, and centrifugal fans.Where the system vacuum requirement is low but the flow requirement is relatively high, the engineer should investigate the use of a centrifugal fan. Centrifugal exhausters are potentially applicable where the system requires a moderate vacuum coupled with relatively high air flow rates. Finally, rotary-lobe blowers should be considered for moderate-to-high vacuum/low-to-moderate flow applications, and regenerative blowers should be evaluated for moderate-to-low vacuum/moderate flow applications. Schematics of these blowers are presented in Figure 3.12.

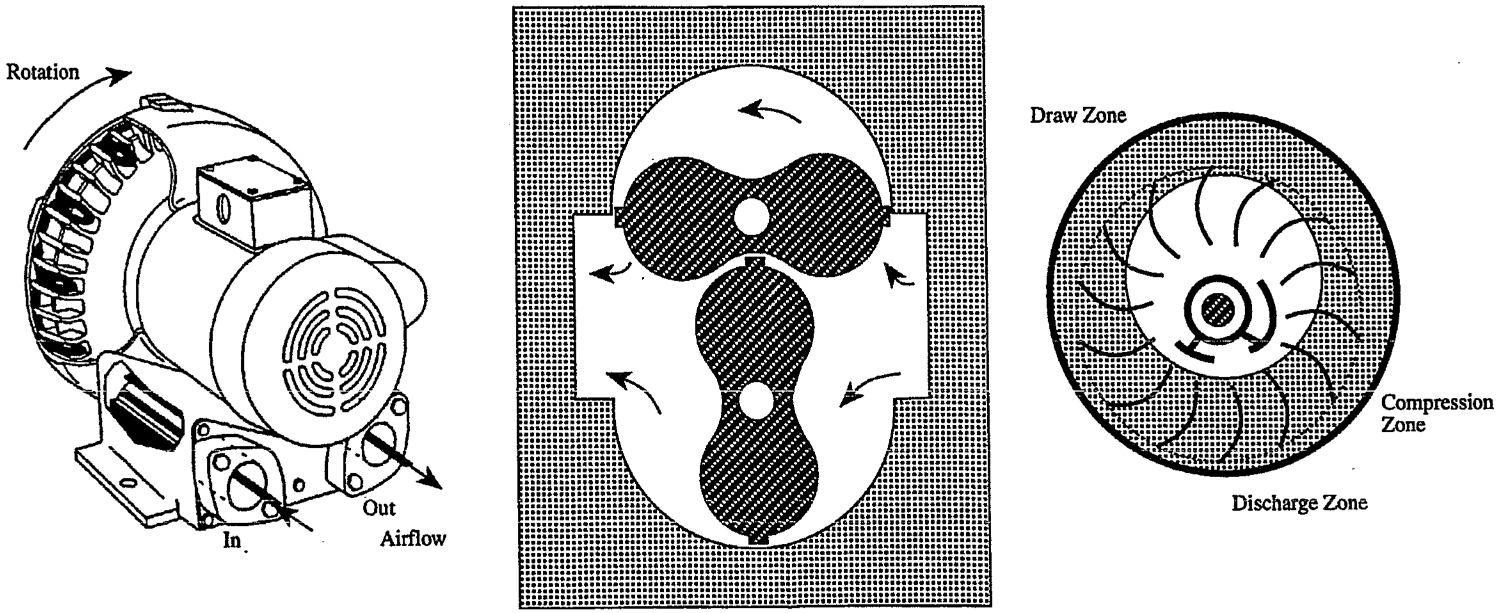
Although detailed descriptions of these blower systems are readily available from manufacturers and suppliers of the equipment, a brief discussion of the blowers and how they function is provided here (US ACE 1995).

Regenerative Blowers. These blowers are typically employed for vapor extraction/bioventing applications requiring less than 203 cm (80 in.) of water vacuum. Regenerative blowers are compact and produce an oil-free air flow. The principle of operation is as follows: (1) a multistage impeller creates pressure through the use of centrifugal force, (2) a unit of air enters the impeller and fills the space between two of the rotating vanes, and (3) the air is thrust outward toward the casing but then is turned back to another area of the rotating impeller. This process continues regenerating the pressure many times until the air reaches the outlet.

Rotary-Lobe Blowers. These blowers are typically used for a medium range of vacuum levels (roughly 50 to 406 cm [20 to 160 in.] of water). During operation of these blowers, a pair of matched impellers which rotate in opposite directions trap a volume of gas at the inlet, and move the gas around the perimeter to the outlet. Rotation of the impellers is synchronized by timing gears that are keyed into the shaft. Oil seals are required to avoid contaminating the air stream with lubricating oil. These seals must be chemically compatible with site contaminants. When a belt drive is employed, blower speed may be regulated by changing the diameter of one or both sheaves or by using a variable-speed motor.

Liquid-Ring Vacuum Pumps. A liquid-ring vacuum pump transfers both liquid and gas through the pump casing. Centrifugal force acting on the liquid within the pump causes the liquid to form a ring around the inside of the casing. Gas is trapped between rotating blades, compressed by the liquid ring, and forced radially inward toward a central discharge port. After each revolution, the compressed gas and accompanying liquid are discharged. Vacuum levels close to absolute vacuum (i.e., absolute pressure equals zero) can be generated in this manner. These pumps generate a waste stream of liquid that must be disposed properly. The waste stream can be reduced by recycling

Figure 3.12
Blower Schematics



Regenerative Blower Operating Principle

Rotary-Lobe Blower Operating Principle

Liquid-Ring Pump Operating Principle

Source: US ACE 1995

the liquid; however, a cooling system for the liquid stream or adequate volume of seal water is typically required to avoid overheating the pump.

Centrifugal Fan. A centrifugal fan (such as a squirrel-cage fan) should be used for relatively high air flow and low-vacuum (less than 76 cm [30 in.] of water) applications. The impellers of a centrifugal fan are typically straight and it is the rotation of these blades that thrusts the air to the outside of the fan casing that allows relatively high volume of air to be processed by this type of blower.

Centrifugal Exhauster. The centrifugal exhauster is constructed with a slight curvature to the blower vanes that enables additional pressure to be developed relative to the centrifugal fan. Its relatively high flow capacity stems from the high rotation speed of the exhauster impeller.

3.3.3.3 Blower Selection

The blower is selected by comparing candidate blower curves to the system curve and the design operating flow/vacuum condition. Where the system curve (in light of the design operating condition) consistently falls beneath a candidate blower curve, the blower is generally considered adequate for the application. To ensure that the blower is not significantly oversized for the system, the design system operating vacuum/flow point should be below, but close to the blower curve.

Discriminating factors in the selection of a blower include:

- *Capital Cost.* The engineer should investigate not only the purchase price of a blower system but other important factors including the degree of complexity required to integrate such a system into the design, added equipment or instrumentation requirements, and space requirements.
- *Operating Cost.* The engineer should consider the costs associated with operating the blower system. Factors to consider include power consumption, reliability of the blower, and maintenance requirements (e.g., oil changes, belt tensioning, manufacturer's parts replacement schedule, etc.).

- *Noise.* The engineer should consider the possible nuisance caused by excessive blower noise (see Section 3.3.3.4). Some blowers require that operators use hearing protection regardless of whether the blower is equipped with silencers.
- *Flexibility.* At the beginning of system operation, higher flows may be needed, requiring greater blower capacity. But as the project progresses, the flow rates may decrease as wells are closed off or as bioventing replaces vapor extraction. For flexibility, the engineer may consider employing a single variable-speed blower or multiple blowers with good turn-down capabilities. However, the range of speeds on some variable-speed blowers may be inadequate. For example, the efficiency of rotary-lobe blowers decreases with changes in speed. Vapor extraction/bioventing systems should also have ambient air intake valves that (among other things) can regulate flow from the subsurface by adjusting the ratio of ambient air to soil vapor while keeping total flow to the blower relatively constant. This type of flow adjustment avoids overheating and maintains the blower within the proper operating range. However, the power requirements are not reduced as soil vapor flow rate and contaminant concentrations in the offgas are reduced, decreasing offgas treatment efficiency.
- *Potential as an Ignition Source.* When there is a possibility that the extracted soil gas may contain concentrations of vapors approaching the lower explosive limit, the blower housing, at a minimum, must be constructed of a nonsparking material. Depending on how the blower is coupled to the motor and the location of the blower, the engineer may also need to specify that the motor meet NEMA 7 requirements (approved for operation in a potentially-explosive atmosphere).

3.3.3.4 Blower Silencers and Acoustics

Depending on the size of the blower and the location of the vapor extraction/bioventing system, inlet and outlet silencers may be necessary to reduce blower noise. Blowers present two noise problems: (1) pulsation within the piping system and (2) noise radiation from the blower itself. Pulsation noise peaks can be severe for large blowers and can result in noise discharges in the high-decibel range.

Silencers are selected based on flow capacities and noise attenuation properties. These devices typically contain chambers with noise absorptive elements. Silencer manufacturers should provide the engineer with an attenuation curve, which is a plot of noise attenuation (decibels) versus frequency (hertz). The objective is to obtain the greatest noise reduction in the range of sound frequencies emitted by the blower.

Also, if the vapor extraction/bioventing system is located within a building, shed, or trailer, the acoustical properties of the wall material should be considered. Tables of absorption coefficients of various building materials versus frequency are published in architectural acoustics references.

Hearing protection must be addressed in the Site Safety and Health Plan. Occupational Health and Safety Administration (OSHA) regulations are applicable to occupational noise exposure. The 8-hour time-weighted average (TWA) sound level is 85 decibels. The TWA represents an action level for requiring that workers be provided with hearing protection.

3.3.4 Tanks and Vessels

Pressure vessels and storage tanks must be designed, constructed, tested, certified, and inspected as noted below (US ACE 1995):

- Atmospheric tanks (0-3.5 kPa [0-0.5 psi]) must be designed to operate at pressures from atmospheric to 3.5 kPa (0.5 psi).
- As part of implementation of a vapor extraction/bioventing system, petroleum, hydrocarbon, or flammable product tanks may be needed to store flammable products. There are some systems, such as those with liquid-phase carbon and on-site carbon regeneration, that recover pure product from the vapor stream. The thermal treatment of offgases often uses a fuel source, such as propane, which must be stored on-site. Also, some vapor extraction/bioventing projects may have an associated groundwater and/or free-product extraction component; thus, free product would be recovered directly from the subsurface.

- The tanks for storage of hydrocarbon products, especially flammable products, must be designed, installed, and specified in accordance with NFPA standards and US EPA regulations governing UST (underground storage tanks) and AGT (aboveground storage tanks). In accordance with federal and local fire codes, tanks containing flammable products must be located at prescribed distances from buildings, property lines, and ignition sources.
- Storage tanks for vapor extraction/bioventing systems are most frequently aboveground. If belowground tanks are employed, they must be double-walled and include leak detection. These tanks must be designed and constructed in accordance with the following standards:

UL-142	Shop Fabricated Aboveground Tanks
UL-58	Underground Tanks
UL-80	Oil Burner Fuel Tanks
API-650	Field Erected Tanks

- Tanks storing in excess of 11,000 L (2,900 gal) of VOCs are not recommended, but if necessary, must be designed in accordance with 40 CFR Part 60.
- Low-pressure tanks (3.5-103.5 kPa [0.5-15 psi]) are designed to operate at pressures above 3.5 kPa (0.5 psi) but not less than pressures specified in the ASME Boiler and Pressure Code, Section VIII, Division 1.

3.3.5 Structural Design Considerations

When determining the design load for a foundation for tanks and vessels, the stability factor and the results of the soil report should be considered in the analysis. Uplift, dead loads, live loads, wind, seismic, snow, thermal, crane, hoist, vehicle, and operating loads should be evaluated as well. Foundation design requires the consideration of underlying soil stability considerations. Some specific guidance is as follows:

- *Wind Load.* Apply to full projection of all equipment, tanks, skids, and platforms in accordance with ANSI Standard A58.1 or local building code if more stringent.

- *Seismic Load.* Estimate in accordance with ANSI Standard A58.1 or local building code if more stringent.
- *Live Load.* Consider the combined total weights of all equipment when full.
- *Anchorage.* Design to resist lateral and uplift forces.
- *Foundations.* Use allowable bearing pressure on concrete of 8,000 kPa (1,200 psi) for design.

3.4 Process Modifications

The vapor extraction and bioventing process can be, and in most cases, must be modified to accommodate initial system performance. Typical modifications to the initial design include installation of additional vapor extraction wells to reflect the distribution of volatile or biodegradable contaminant mass determined to be present at the site. As discussed previously, the number of extraction wells required to be effective on a specific target area is based initially on pilot test results. However, as the vapor extraction or bioventing system operates, contaminant mass distribution, soil moisture content, and biological activity will vary substantially. This necessitates that the engineer provide for future modifications to the design that may be required to maintain a maximum mass removal rate over the entire affected area during the life of the remedial project.

This section focuses on modifications that can be made during the design phase and improvements to existing systems.

3.4.1 Designing for Operational Flexibility and Expandability

In many cases, minor modifications to a simple vapor extraction system can have significant impacts on the mass removal rate. If the engineer keeps this in mind during the design process, then minor process modifications can be made at minimum cost.

Wells should be designed for maximum flexibility. Providing each wellhead with separate flow measurement and control capabilities facilitates flow balancing and variation. For sites with large vented intervals, designing wells with two or more discrete screened sections allows flow to be targeted as a function of depth.

In many cases, vapor extraction systems do not perform as expected with respect to mass removal rate or time to closure. To have a significant impact on these parameters, additional vapor extraction wells could be required. After trying variable flow rates, zone operation, etc. without significant increases in the mass removal rate, and if a mass of volatile soil contamination is known to still exist (by virtue of soil sampling, consistently high concentrations of VOCs in certain wells, or other means), additional wells may be required to achieve closure goals in a reasonable time frame. Accommodating additional wells requires that the piping, manifolding, vacuum blower, and air emissions equipment be specified such that additional air flow and contaminant vapors can be properly handled by the system. In the case of dual-phase vapor extraction, additional water piping, manifolding, and vacuum pump capacity may be needed.

For example, designing a pipe manifold to accommodate additional vapor extraction wells may add little, if any, additional cost, but would be critical in allowing the additional air flow should additional wells be needed to accelerate the remediation. Additional "T" fittings and valves (routed to blank pipe ends) could be added to the main manifold near the vapor extraction blower intake for additional wells should they be needed in the future.

Additional buried piping will be required to connect new wells to the vapor extraction system. Labor and equipment for excavation and resurfacing typically comprise the majority of the costs for installing buried piping. Materials are a relatively minor cost. Therefore, if the engineer specifies additional (initially unused) buried transmission piping in piping trenches, the cost of tying into those pipes with additional wells will be minimized. Typically, additional buried piping is only placed when routing the transmission piping through zones of significant contaminant mass, not in peripheral areas. However, if site logistics dictate few transmission routes or if only limited site characterization data are available to define the contaminant mass location, then additional buried piping may be an inexpensive insurance policy in the event that additional wells are needed at a later date to achieve closure goals. When power supply and electrical control wiring is placed in the same trench, separate conduits for power and control wiring are necessary and the conduits should not be placed less than 12 inches apart.

This approach is particularly applicable to piping beneath buildings, into remediation equipment buildings, or through existing structures at the site. For example, the placement of sleeves and pipe stubs in concrete slabs to accommodate future needs will add little cost during construction compared to excavation and coring at a later date. This same concept is applicable to electrical and control wiring conduits, in the event additional power or control wiring is needed in the future. Whenever empty conduits are installed, care must be taken to ensure they are sealed to prevent soil, debris, or water from accumulating in them prior to future use.

Vacuum blower characteristics, (pump vacuum or air flow capacity) may limit the effectiveness and potential expansion of an existing vapor extraction system. In this case, the available capacity may be focused on fewer wells at higher vacuums and lower total flow rates. This may increase the mass removal rate. If these inexpensive modifications are not successful in increasing the mass removal rate, additional vacuum or air handling capacity may be needed. The engineer must consider the blower curve (which relates the induced vacuum versus the air flow rate) for the existing blower to evaluate the capacity for more air or a higher vacuum condition. The existing blower or blowers may be able to perform at the flow rate and vacuum condition required for maximum mass removal. If not, a different blower will be required. For larger systems, several small blowers instead of one very large blower may provide more operating flexibility.

Clearly, if the air flow rate and quality of vapors changes significantly, the capacity and adequacy of the existing vapor treatment system must be evaluated and modified to accommodate the changing process flow. In some cases, the vapor treatment equipment may be eliminated or downsized as the remedial project progresses, depending upon the air discharge permitting requirements applicable to the site. However, when evaluating a change in air treatment capacity, VOC contaminant spike concentrations occurring after a period of inactivity (1 week to 1 month depending upon the ambient temperature and the volatility of the contaminant) for each well must be used to ensure maximum concentrations will be adequately treated.

The use of control valves and the design and placement of manifolds must accommodate the need to target residual hot spots as the project progresses. This is particularly important on larger sites where there is a temptation to manifold several wells into one vapor extraction pipe. With this configuration, balancing the air flow among the wells is difficult even with control valves at each wellhead. This is because each well will produce a different vapor flow rate at a given valve setting and the flow rate from each well is also affected by the valve setting at another well on the same manifold. Therefore, the initial design needs to consider how each area of the site could be targeted at future stages of the project. Where practical, individual pipes for each vapor extraction well are recommended. Individual pipes also simplify operations since all the pressure and flow monitoring and gas sampling can be performed in one location.

3.4.2 Pulsing

Pulsing of vapor extraction wells is another modification that can be used in the later stages of remediation to reduce offgas treatment costs. Pulsing involves the periodic application of vacuum to each vapor extraction well. This may be accomplished by pulsing the entire system with on/off cycles or by manually or automatically operating control valves for each well or manifolded-well network. In the late stages of remediation, where diffusion limits mass removal, pulsing can maximize the contaminant concentration within the offgas and minimize the duty cycle of the offgas treatment system. However, the overall mass removal will always be less in pulsed operation than with a corresponding continuous-flow operation.

On/off pulsing of the entire system creates stress on the motor starter for the vacuum blower. If this approach is chosen, the motor starter must be designed for this purpose and be capable of handling high-voltage switching on a continual basis .

Pulsing may allow the initial selection of a smaller vacuum blower in terms of air-handling capacity. For example, if a total of 50 vapor extraction wells comprise the system, but only 5 are pulsed at a time, the blower may be sized to accommodate up to 5 wells at a time if the necessary automatic valving is provided for each 5-well group. More importantly, the blower may be selected for a wider vacuum range than may be needed initially. The additional cost of valving, especially automatically-operated valves, must be considered in the decision to include pulsing to improve the overall mass removal rate.

Finally, piping, valves, and other components will be exposed to the stresses of pulsing from a high vacuum to atmospheric pressure multiple times over the course of the project. Therefore, these components must be constructed of materials capable of withstanding the stress of pulsing.

3.4.3 Adapting to Nonideal Situations

3.4.3.1 Anisotropy

Anisotropy refers to a difference in hydraulic or pneumatic conductivity with a change in direction within the subsurface. For example, stratified clay soils may be present above and below a sandy layer. In this case, air or water flow would be favored in the horizontal direction (in the sand layer) and limited in the vertical direction. In such cases, the process of vapor extraction can be modified to focus on the soil type containing residual contaminants in excess of the closure goal. This is effected by adjusting the screened interval of the extraction wells to intercept only one type of soil or by using multiple screened intervals in one well that focus vapor extraction air movement on zones with comparable conductivities.

Where sand or clay lenses are abundant, careful evaluation of the location of the contamination is needed to account for preferential flow layers. Site hydrogeology can be used to advantage in some cases. For instance, when contamination is perched atop a clay lens in a perched water table, dual-phase vapor extraction may be used in that area to remove a continuing source of groundwater contamination.

3.4.3.2 Short Circuiting

Short circuiting of air flow patterns around contaminated zones can limit the effectiveness and lengthen the time to achieve closure goals. Short circuiting is caused by anisotropic conditions which are either natural or man made. Classic examples of man-made anisotropic conditions are buried utilities, such as storm or sanitary sewers; petroleum, natural gas, or water pipelines; or cable television, telephone, or electrical wiring. Considering that the backfill for these buried utilities is typically sand and that compaction of native fill may not be extensive after construction, almost all remediation sites will have such man-made potential short circuit pathways.

The first step in understanding the potential for, and guarding against, short circuiting is to prepare several detailed cross sections of the site showing the soil types, buried utilities, and contaminant distribution. Planning for vapor extraction well locations and depths must account for the most likely air flow patterns in response to applied vacuums, or in the case of dual-phase extraction, the most probable air and water flow patterns.

When a vapor extraction system is designed to effect mass removal in a shallow soil (less than 3 m [10 ft] deep), short circuiting to the surface may occur. In this case, a surface cover may enhance vapor penetration into contaminated zones and limit short circuiting to the soil surface. One simple way to provide a surface cover is to apply 12 to 24 mil polyethylene plastic sheet covered with a thin layer of sand (less than 10.25 cm [4 in.]); however, unless the edges of the polyethylene cover are keyed into the soil, the cover will have little effect on the underlying air flow pathways. Paved areas may limit short circuiting to the surface, but unless the concrete or asphalt is relatively new and devoid of cracks and other penetrations, significant short circuiting may still occur.

To confirm short circuiting is not occurring, a gas tracer test can be completed (US EPA 1996). A conservative (nonreactive) tracer gas, such as argon or helium is injected at a known rate in one well or drive point within the contaminant mass (unused vapor extraction or monitoring well) and the concentration of the tracer gas is measured at a series of points as it moves through the contaminated area and into a vapor recovery well. If no tracer gas can be recovered, it is likely that the majority of the air coming into the recovery well is not coming from the contaminated zone and short circuiting is occurring. To remedy this situation, new well points (to let in air at strategic points) or new vapor extraction wells (to collect vapors at different points) may be necessary.

3.5 Posttreatment Processes (Offgas Handling)

3.5.1 Technology Descriptions

As discussed in Section 3.12, the need for offgas treatment and the associated regulatory requirements vary greatly among sites. Yet, offgas treatment can account for half of the overall system construction and operation costs.

A vapor extraction/bioventing system engineer can choose from among a wide variety of offgas treatment technologies. Complicating selection of the most cost-effective treatment technology is the fact that offgas treatment concentrations and composition change with time. During the initial period of remediation offgas concentrations are highest; midway in the remediation offgas concentrations tend to decrease exponentially; and in the final stage offgas concentrations are relatively steady. Therefore, a cost-effective technology for initial conditions may not remain so throughout.

In general, offgas treatment technologies can be classified as one of three types: physical, thermal, and biological. Physical offgas treatment technologies are typically based on the adsorption of vapor-phase contaminants onto a medium or resin. Contaminants are not destroyed (until the adsorption medium is regenerated) but only transfer phase. Vapor-phase carbon is the most common of these technologies. Thermal treatment technologies rely on the thermal oxidation of vapor-phase contaminants. Thermal oxidation (flares), catalytic oxidation, and internal combustion engines are all variations of basic thermal treatment processes. In direct thermal oxidation, contaminants are heated until they oxidize. Biological treatment is based on the biological oxidation of vapor-phase contaminants. Equipment used to biologically treat vapor-phase contaminants is typically termed a "biofilter".

Transfer of contaminants from one media to another must be considered to minimize impacts to human health and the environment during remediation. Cross-media transfer issues have been elaborately covered in a recent US EPA publication, *Best Management Practices (BMPs) for Soil Treatment Technologies*, EPA 530-R-97-007, May 1997.

Table 3.6 presents a comparative summary for various offgas control technologies. The following paragraphs give a detailed explanation for each of these treatment technologies (US ACE 1995).

3.5.1.1 Vapor-Phase Carbon

Vapor-phase carbon can remove many classes of organic compounds including aromatics, aliphatics, and halogenated hydrocarbons. Some VOCs (such as vinyl chloride) cannot be removed by carbon so the applicability of

Table 3.6
Offgas Control Technology Selection Issues

Technology	Implementation	Operation Concerns	Reliability	Most Cost-Effective Application
Flare	Difficult. Requires extra energy source, controls, and permitting. May be community concern in some areas. Vendor units are readily available. Halogenated compounds may require added treatment.	Requires a trained operator because of added I&C complexity.	High. As long as system is operating, provides high degree of contaminant destruction.	Used for flow rates greater than 50 scfm. Most cost-effecitve or mass removal of more than 10 lb/day and concentrations > 2,000 ppm.
Catalytic Oxidation	Difficult. Requires extra energy source, controls, and permitting. May be community concern in some areas. Vendor units are readily available. Halogenated compounds may require added treaetment.	Requires a trained operator because of added I&C complexity.	Moderate to high. Catalyst life needs to be considered based on contaminants being treated. Some metals and chlorine can poison the catalyst.	Used for flow rates greater than 50 scfm. Most cost-effective for mass removal rates of more than 10 lb/day and concentrations < 2,000 ppm.
IC Engine	Moderate. Combined engine/offgas treatment simplifies design and controls. Vendor units generally available.	Relatively simple operation because of integrated system.	Moderate to high. Requires proper mix of vapor/air. Engines sensitive to changes in moisture.	Most cost-effective for lower flow rates (50 to 100 scfm) with total VOC concentrations > 4,000 ppm.
Vapor Phase Carbon	Easy. Requires little additional controls. (Sometimes a heater is required). Readily available equipment.	Simple mechanical operation. Offgas sampling is required to assess breakthough.	Reliable for most contaminants. Reliability depends on degree of offgas and breakthrough monitoring.	Can be applied to a wide range of air flow rates. Most cost-effective for mass removal rates < 5-10 lb/day.
Adsorption Resin	Easy. Requires few additional control. Tends to be a specialty product and so less available.	Simple mechanical operation. Offgas sampling is required to assess breakthrough.	Reliability depends on type of contaminants being treated.	Tends to be applied only when vapor-phase carbon is not effective.
Biofilter	Easy. Simple controls. However, relatively few commercial units available. Primarily used for petroleum hydrocarbons.	Simple operations. Some control of offgas temperature and moisture content required. Because of relatively low reliability, a signficicant amount of offgas monitoring required.	Low. Subject to upsets based on changes in offgas concentrations, compostion.	Can be applied to a wide range of flow rates. Most effective for total VOC concentrations from 100 to 1,500 ppm.

carbon should be checked prior to selecting it as a vapor treatment method. Many vapor extraction systems utilize granular activated carbon in flow-through reactors. When properly designed, these systems are relatively simple to operate. Adsorption is due to chemical and physical attractive forces between liquid or gas-phase molecules and the molecules of the solid adsorbent. Activated carbon is commonly manufactured from raw materials, such as wood, coal, coke, peat, and nut shells.

A carbon adsorption design usually includes multiple adsorbers, in which case the columns are operated either in series or in parallel. The series arrangement is generally operated so that the secondary acts as a backup when breakthrough occurs on the primary column. When the first column is removed from service, the second column is moved up to the first position, and the new column (or regenerated column) is installed in the second position. Carbon vessels must be capable of withstanding the temperatures/pressures needed to mobilize site contaminants.

Adsorption is normally a reversible process. That is, under suitable conditions, materials that have accumulated in the carbon can be driven off, and the carbon can be reused. Thermal reactivation is the most widely used regeneration technique. In vapor extraction systems where carbon usage is low, on-site regeneration will not be cost-effective, and the spent carbon should be either disposed or regenerated off-site. For larger, long-term vapor extraction systems, on-site regeneration should be considered. The decision to regenerate on-site would be based on a complete life-cycle cost analysis. The concentration threshold for considering on-site regeneration is typically between 50 and 500 ppm for a project duration of several years. If possible, the engineer should estimate the total carbon usage for the life of the project and compare the carbon cost with the capital and operation and maintenance cost of the regeneration system. A similar economic analysis could be performed for comparison with catalytic and thermal oxidation.

Carbon becomes less efficient with high relative humidity. Activated carbon relies on an extensive network of internal pores to provide surface area for adsorption. Although there is not direct surface attraction, the water vapor occupies internal pore space due to capillary condensation. A relatively small increase in temperature will improve carbon efficiency by reducing the relative humidity (as a rule of thumb, a 10°C [18°F] increase in temperature will reduce relative humidity from 100% to below 50%), but a large temperature increase would be detrimental to the carbon efficiency. A heat exchanger or chiller could be used to lower the temperature.

3.5.1.2 Adsorption Resins

Adsorption resins are commercially available for use in collection of polar hydrocarbons and solvents that are difficult to collect on granular activated carbon. While these materials are traditionally used in wastewater applications, they may be adapted to use on vapor streams. The initial resin expense can be high, but they are usually regenerated to recover solvents or other materials, providing an offsetting return and saving on disposal costs. One advantage of resins over activated carbon is that they can safely handle acetone and other ketones, that decompose exothermically on granular activated carbon and can ignite the vapor stream.

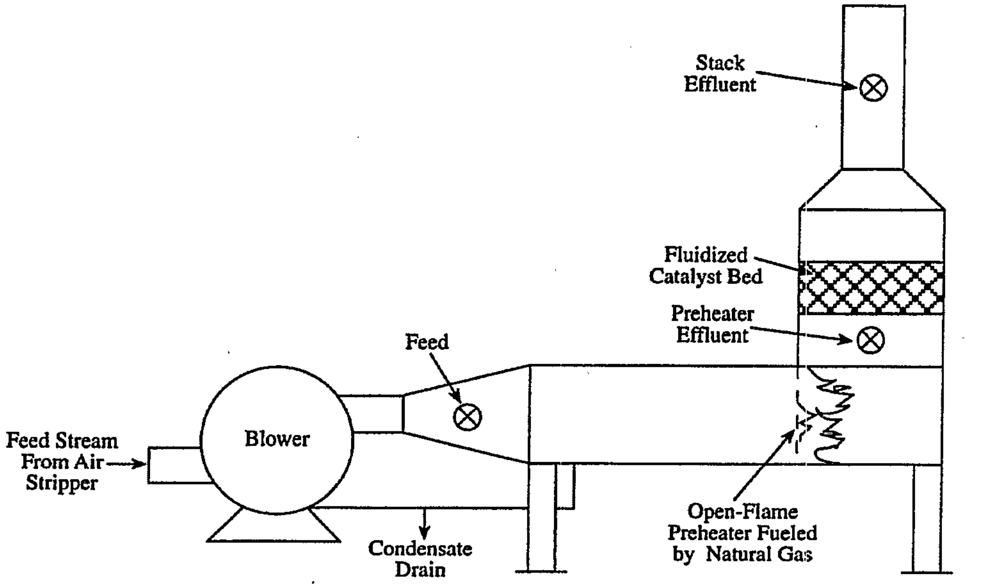
3.5.1.3 Catalytic Oxidation

Catalytic oxidation is a common means of offgas treatment in vapor extraction systems. The catalyst, often platinum, lowers the activation energy of the oxidation reaction allowing it to proceed at a lower temperature, usually between 288 and 371°C (550 and 700°F). The lower combustion temperature results in significant energy savings. Catalyst manufacturers typically claim 95% conversion of non-methane hydrocarbons. A complete catalytic oxidation system may include a burner, a heat exchanger, the catalytic reactor, and a stack (see Figure 3.13).

Catalytic oxidation is subject to several limitations. The following contaminants are known catalyst deactivators and contribute to shortened catalyst life: lead, mercury, zinc, arsenic, antimony, copper, tin, iron, nickel, chromium, sulfur, silicone, and phosphorus. Catalytic oxidizers will overheat if the fuel content of the vapor extraction air stream is too high. This should be considered at sites where the vapor levels exceed 10% of the lower explosive limit. Under favorable conditions, catalysts need to be replaced approximately every three years.

Recent advances in catalyst technology have resulted in catalysts that are resistant to halogenated compounds. However, catalytic oxidation of halogenated hydrocarbons generates acidic vapors that require treatment. Consequently, scrubbers are typically installed in such systems. Scrubbers can add significant capital and operating costs.

Figure 3.13
Schematic of Catalytic Oxidation Unit

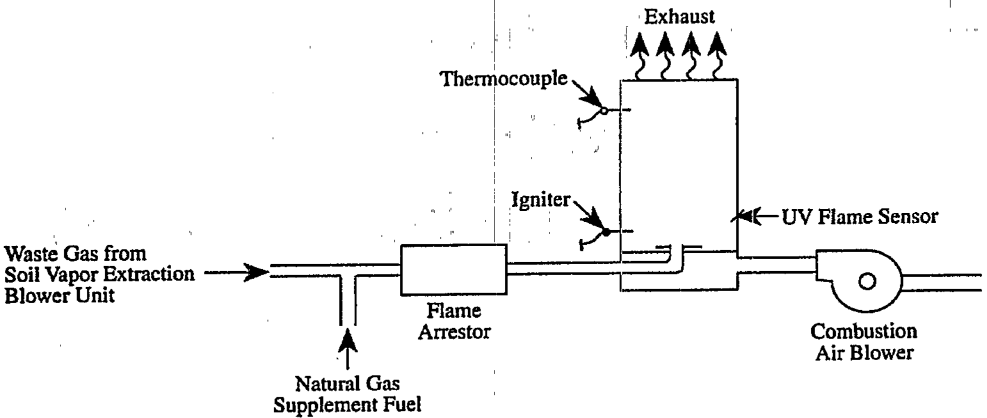


3.5.1.4 Thermal Oxidation

Thermal oxidation involves heating the air stream to a temperature high enough for combustion (Figure 3.14). Thermal oxidizers typically operate between 900 and 1,600°K. They are generally simpler and more versatile than catalytic systems because there is no need to be concerned with compatibility of the compounds with the catalyst. Thermal units could be used initially and as long as concentrations remain high. However, they are much less efficient after concentrations decline because supplemental fuel is required at low concentrations to maintain the relatively high operating temperature. Thus, in most vapor extraction applications, thermal oxidation is not economical over the entire life cycle of remediation. Combined thermal/ catalytic oxidation units are available to accommodate changing concentrations in the vapor extraction offgas.

Significant cost savings can be realized by utilizing heat recovery techniques. Primary heat recovery exchanges heat from the air exiting the combustion chamber with the air entering the combustion chamber. Secondary

Figure 3.14
Flaring Process



heat recovery uses the heated exhaust to preheat plant air or produce steam. As with all heat exchange systems, there is a trade-off between heat recovery efficiency and the size, or more precisely the surface area, of the heat exchanger.

A scrubber could be used in a vapor extraction system to control acid gases generated by thermal or catalytic oxidation. Scrubbers reduce acid gases and particulate in an air steam by transferring these compounds to a circulating liquid stream. For acid gas control, the pH of the liquid would subsequently be neutralized. Scrubbers are available in various configurations including venturi, spray tower, packed-bed, fluidized-bed, and sieve tray.

A flare unit or even an internal combustion engine are modified forms of furnace-style oxidation units. Both of these forms of oxidation can process very rich hydrocarbon streams; they are intended to operate in the explosive range, although fuel still may be added. Flares are rarely used in vapor extraction/bioventing offgas treatment because the fixed installation costs are usually high and the influent hydrocarbon concentration is rarely high enough to justify the fixed installation cost.

3.5.1.5 Internal Combustion Engines

Internal combustion engines (specifically diesel-fuel-driven engines) have been marketed to perform both the vacuum pump function and the offgas treatment. The well(s) is connected to the air inlet of the engine, which operates on a test stand to combust the hydrocarbons from the well. Diesel engines are used because they are better able to operate on a continuous basis. This approach offers competitive installation costs but is usually more difficult to permit and operate because emissions from the engine exhaust must be monitored, and the engine can be sensitive to abrupt changes in soil conditions (especially moisture).

3.5.1.6 Condensation

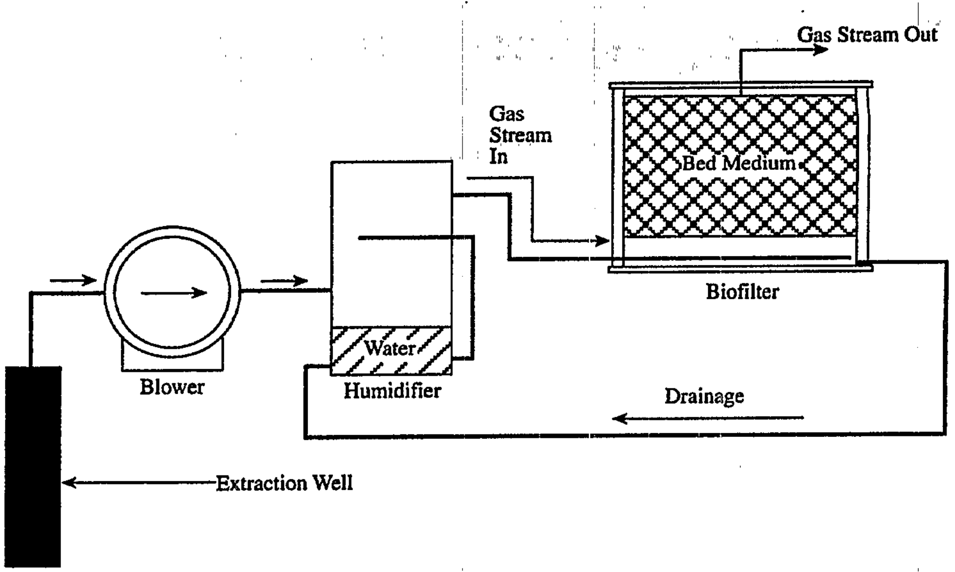
Condensation can sometimes be considered for use if the hydrocarbons are (1) sufficiently high-boiling to be readily condensable and (2) present in high concentrations. While some product recovery is possible with this approach, materials that are readily condensable do not usually volatilize well at typical soil temperatures. This technology is better suited to applications where heating is used to increase the hydrocarbon removal rate from the subsurface.

3.5.1.7 Biofilters

Biofilters have been used for odor control for industrial processes since 1953. An estimated 500 biofilters are currently in service in Europe, and 100 are in service in the United States, mainly for odor abatement. Biofiltration to reduce hazardous air pollutant emissions is a more recent development of the 1980s (Severin, Shi, and Hayes 1994). Use of biofilters to treat contaminated air streams, such as vapor extraction offgas, is expanding due to its low cost relative to other alternatives, such as thermal incineration and carbon adsorption (Govind et al. 1994; Severin, Shi, and Hayes 1994; Kosky and Neff 1988). A typical biofilter process is shown in Figure 3.15.

A variety of support media have been used in biofilters including soil, peat, compost, oyster shells, and pelletized activated carbon. A limitation of biofilters using these materials is the inability to control biomass buildup without periodically replacing the filter media. Improved support media are currently being developed such as ceramic filter material with straight

Figure 3.15
Schematic of Vapor Extraction Offgas Treatment with a Biofilter



passages. Biomass periodically sloughs off from the straight passages, resulting in a self-cleaning medium.

The straight passages within the support medium can also have a carbon coating. This helps protect the microorganisms from shock loadings because high contaminant concentrations will initially adsorb to the carbon and later desorb when air-phase contaminant concentrations are low (Govind et al. 1994).

3.6 Process Instrumentation and Controls

3.6.1 Purpose

The most important purpose of instrumentation and controls is safety. Instrumentation can detect unsafe conditions, shut the system down safely, and notify the operator. The health and safety of personnel operating the system or those nearby is of primary importance. Therefore, the minor cost of safety monitoring and shutdown alarm devices is mandatory. Emergency shutdown switches should be easy to find and operate. The engineer must specify these components and ensure they are installed and function properly at startup and conduct periodic tests to ensure continued functionality.

Other purposes of instrumentation and controls are to monitor the performance of the vapor extraction or bioventing system and to minimize operator labor and costs. The engineer must ensure that safe operating conditions are maintained and that the design conditions for each system component (vapor extraction, bioventing, air treatment or air/water separators, and water treatment equipment) are maintained. Ultimately, the level of instrument sophistication depends on complexity of the process, remoteness of the site, and how long the system is expected to operate.

3.6.2 Instrumentation Selection

Instrumentation refers to the sensors used to detect a change in conditions in the field, along piping runs, or at the collection and treatment equipment. Sensors are categorized as responding to either physical, chemical, biological, or thermal inputs.

For a typical vapor extraction or bioventing system, the following sensors are permanently affixed to the system:

- *Physical* — air flow sensors, air flow meters, high-level switches on air/water separator tanks, vacuum gauges, pressure gauges, vacuum switches, pressure switches, etc.; and
- *Thermal* — thermistors inside rotating motors or control panels that shut down motors when thermal overloads occur.

Portable instruments that are typically used to monitor a vapor extraction or bioventing system are:

- *Chemical* — portable PIDs, FIDs, lower explosive limit (LEL) meters, explosimeters, oxygen sensors; and
- *Biological* — portable oxygen, carbon dioxide sensors, in situ respirometry equipment.

Instrument selection must based on the anticipated operating conditions and ranges (e.g., physical limits for float switches, chemical concentrations, temperature ranges, etc.) that could exist during operations, available power, weather conditions (if outside), exposure to water (weather or other processes in the equipment room or compound), compatibility with remote control systems, telemetry systems, etc.

3.6.3 Controls and Alarms

Sensors provide a signal to a control system or directly initiate other actions. In a simple vapor extraction or bioventing system, controls will consist of relays that turn equipment, such as blower motors, on or off in response to certain conditions. Conditions that should result in system shutdown include LEL conditions, high water in the air/water separator tank, vacuum exceeding design conditions, or temperature overload of the blower motor. System shutdown can also be tied to unauthorized entry into an equipment enclosure or building.

More sophisticated systems use programmable logic controllers (PLCs) that replace relay switches and perform the same function, but can be programmed to provide a wide variety of control functions in response to sensor input. PLCs are typically more cost-effective than relays when more than 20 relays are needed. Recent advances in PLC technology now enable cost savings even on simple systems.

If VOC concentrations measured during site characterization, soil sampling, or pilot testing indicate the potential for VOCs to be present in excess of the LEL or OSHA threshold limit values (TLV), an LEL alarm (audible and flashing light) should be installed and tested periodically to ensure functionality.

Another useful alarm function is to monitor for high temperatures in the exhaust stack, indicating the blower is operating beyond the design range or rapid vacuum losses, which could indicate a broken pipe. Finally, a simple and inexpensive smoke detector is recommended for all enclosed equipment buildings or equipment containers. Containers may create confined spaces as defined by OSHA, and special portable monitoring or permanent detectors and alarms may be needed to meet OSHA entry requirements.

Control functions are related to the system piping and other components on the piping and instrumentation (P&I) diagram. The P&I diagram is a crucial part of the design drawing package and shows the interrelationships and control features of the entire system. Instrumentation is also shown as well as how the output of the various sensors is used to control equipment, switches, valves, and other equipment.

3.6.4 Remote System Monitoring/Telemetry

Remote monitoring has been used in industrial settings for years to control complicated automated processes (i.e., robotics). Recently, several remote system monitoring devices have been developed and used effectively to monitor remediation system performance from a remote location. Each device requires a telephone line or cellular phone to advise a remote operator of a system malfunction. The simplest device can call a pre-programmed telephone number (or pager number) if a system alarm occurs. Another simple device can send a fax to a pre-programmed fax number with daily operational data or immediately in the case of an alarm. The most sophisticated devices can send current sensor data to a remote computer which, when fitted with the proper software, can provide a visual representation of system performance. Many of these software-driven systems can also be used to troubleshoot the system from a remote location. If selected and installed properly, most of these systems can minimize the day-to-day attention necessary for safe system operation.

3.7 Safety Requirements

This section presents the basic safety requirements of a vapor extraction or bioventing system. The requirements presented here are not exhaustive; they are intended only to provide the engineer with a list of minimum safety requirements. A process safety review is recommended and may be required if the system emissions are permitted as stipulated by the Clean Air Act. To this end, Appendix B includes an example process hazard review form and a list of guide words to be used to identify possible safety hazards under conceivable operating and nonstandard conditions.

3.7.1 Designing for Construction Safety

The vapor extraction/bioventing system engineer can minimize hazardous conditions during the construction phase by evaluating the steps necessary for construction and associated potential hazards. Through good design, the engineer can eliminate potentially unsafe or difficult assembly procedures and reduce (1) the time required for construction and (2) the risk of injury to site workers.

For example, OSHA regulations stipulate that a poorly-ventilated enclosure, where ingress and egress is limited due to small openings or obstructions, be considered a "confined space" (40 CFR, Part 129). Confined spaces can be quite hazardous and require specific permits, and strict, time-consuming procedures. Therefore, if an engineer increases the size of access doors, makes below-grade vaults no deeper than 46.75 cm (18 in.), and relocates obstructions to ingress and egress, a confined space will not be created and a safer system will result.

Trenching for vapor extraction and bioventing systems need not be installed below the frost line if piping is sloped back toward extraction wells to facilitate back flushing and gravity drainage of condensate. In extreme cold conditions, the lines may need to be insulated. Shallower trenches can minimize the potential for caving. Providing sufficient working room in well vaults to allow access to vapor and flow monitoring points can minimize the potential for back and hand injuries.

Most regenerative blowers used for vapor extraction generate significant noise levels. The engineer must consider the decibel rating of each blower (or other piece of equipment) and persons who may be exposed to the noise. For example, technicians adjusting the system while it is operating will need hearing protection, especially when the blower is located inside a containment building or enclosure. Of particular concern is the noise level of vapor extraction systems in residential neighborhoods. In some cases, sound insulation may be required to minimize noise pollution.

Planning the sequence of construction and specifying it in the plans and specifications can minimize site disturbance and, for active sites where other activities are ongoing, minimize the potential for injuries to site personnel who are unassociated with the remediation project. Specifying material storage locations, no smoking areas, and temporary fencing around the construction area will also lessen the potential for injuries.

3.7.2 Building Code

The Uniform Building Code (UBC) has been developed to regulate the construction of structures in the United States. Many regions, states, counties, and cities have additions or modifications to the UBC that regulate the construction of buildings, buried piping, sewer discharge lines, etc. These codes must be adhered to, as applicable, for vapor extraction and bioventing systems. In fact, in most locations in the United States, a building permit must be obtained from the local regulatory authority prior to initiating construction.

With few exceptions, design drawings and supporting structural calculations must be submitted to the proper building officials for review as part of the permitting process. Such submittals are in addition to those required by the environmental regulatory agency. All state laws and most regulatory authorities require that the design be completed and certified by a professional engineer, licensed in the state where the project is located and competent in the specific area(s) of expertise of the work shown on the plans and specifications.

With the increase in number of remediation projects in all parts of the country, some local building officials have developed regulations and codes specific to this type of activity. Contacting the local building department prior to design will save a significant amount of time and money compared to the seemingly endless iterative process of revisions that may be required if this simple step is ignored.

3.7.3 Electrical Code

This section has been duplicated from a guide published by US ACE (1995). The guide establishes the basic requirements of materials, equipment, and installation for electrical systems.

Like all systems included in the design, the basic electrical-related considerations that will affect the overall design must be reviewed at the beginning of the design phase. Electrical system planning should include any power needs that can be anticipated. In addition to technical and statutory needs, the design philosophy must emphasize the following:

- safety of personnel and equipment,
- flexibility for expansion, and
- accessibility for operational and maintenance needs.

The following electrical-related topics should be covered by the design plans and/or specifications:

- electrical conduits,
- electrical duct runs,
- buried ducts,
- trenching and backfilling procedures,
- overhead power lines,
- lighting fixtures,
- emergency lighting,
- motors,
- system voltage,
- package equipment, and
- electrical heat tracing.

A list of applicable reference codes, standards, and specifications for electrical systems is included in Appendix B.

3.7.3.1 Area Classifications

The National Electrical Code (NEC) stipulates area classifications that are a crucial part of the electrical design for all vapor extraction, dual-phase, and bioventing systems. All electrical equipment involved in the vapor extraction/bioventing system must be selected and installed in accordance with the requirements of the classifications of the various areas. Depending primarily on the expected presence of explosive vapors, the areas to be categorized fall into one of the following NEC classifications:

- Class I, Group D, Division 1;
- Class I, Group D, Division 2; or
- Unclassified.

All area classifications should consider long-term needs, such as future changes/modifications that may be made to the system.

3.7.3.2 Definition of Classified and Unclassified Areas

All control rooms, battery rooms, and switch houses shall be designed as unclassified areas. Where these rooms are located within, or adjacent to, a hazardous area, the rooms shall be pressurized in accordance with NFPA 496. All such pressurized rooms shall be provided with means of egress directly to the outside without passing through the hazardous area. Where this is not practicable, a suitable single-door system shall be installed. Installation of double airlock-type door systems is discouraged.

Areas shall be physically separated from each other, and classified as Class I, Division 1; Class I, Division 2; or Unclassified. These classifications are as defined in the NEC. Unclassified zones shall be maintained at a higher pressure than Division 2 zones, and Division 2 zones higher than Division 1 zones in order to prevent hydrocarbon vapors from migrating into areas containing ignition sources. Differential pressure switches with alarms shall be installed between adjacent fire zones where assurance of a positive differential pressure between fire zones with different classifications is required.

Classification of an area as Division 1 or Division 2 requires careful consideration of the process equipment in that area, the physical characteristics of hazardous liquids/gases, the amount of ventilation provided to the area, and the presence of various equipment, such as piping with valves, fittings, flanges, and meters. The volume and pressure of the gases or liquids involved in the process should also be considered.

The classification of Class I hazardous locations as Division 1 or Division 2 is not a straightforward task. NFPA has developed a recommended practice (NFPA 497) that should be followed.

In summary, the distinguishing features of Divisions 1 and 2 and Unclassified areas are as follows:

> Class I, Division 1 locations may be distinguished by an affirmative answer to any one of the following questions:
>
> - Is a flammable mixture likely to exist under normal operating conditions?
> - Is a flammable mixture likely to exist frequently because of maintenance, repairs, or leakage?

- Would a failure of process, storage, or other equipment be likely to cause an electrical failure simultaneously with the release of flammable gas or liquid?
- Is the flammable liquid or vapor piping system in an inadequately ventilated location, and does the piping system contain valves, meters, seals, and screwed or flanged fittings that are likely to leak significant volumes in proportion to the enclosed space volume?
- Is the zone below the surrounding elevation or grade such that flammable liquids or vapors may accumulate?

Class I, Division 2 locations may be distinguished by an affirmative answer to any one of the following questions:

- Is the flammable liquid or vapor piping system in an inadequately ventilated location, and is the piping system (containing valves, meters, seals, and screwed or flanged fittings) not likely to leak?
- Is the flammable liquid or vapor being handled in an adequately ventilated location, and can liquid or vapor escape only during abnormal conditions such as failure or rupture of a gasket or packing?
- Is the location adjacent to a Division 1 location, or can vapor be conducted to the location as through trenches, pipes, or ducts?
- If positive mechanical ventilation is used, could failure or abnormal operation of ventilating equipment permit mixtures to build up to flammable concentrations?

Outdoor installations, usually consisting of open pipeways, are adequately ventilated and do not justify a Class I, Division 2 classification because only a catastrophic failure would result in an explosive concentration of gas or vapor. However, each specific case must be reviewed carefully before a classification is assigned.

Unclassified locations are defined as follows:

a. Locations that are adequately ventilated (including most outdoor installations) where flammable substances are contained in suitable, well-maintained closed piping systems which include only pipe, valves, fittings, and flanges are considered nonhazardous. Most outdoor open pipeways are considered nonhazardous. Areas that are not ventilated, provided the piping system is without valves, fittings, flanges, or similar appurtenances, are also considered nonhazardous.

b. Locations containing permanent sources of ignition, such as fired boilers, pilot lights, equipment with extremely high surface temperatures (above the ignition point of the gases in the area) are not deemed hazardous when considering electrical installations because the electrical equipment would not be the primary source of ignition.

3.7.3.3 Application of Area Classification

Hazardous locations exist in many areas of a facility where flammable liquids or gases are processed. All of these locations should be identified and equipped with appropriate electrical equipment to ensure safety of personnel and facilities. There are three basic questions to be answered in classifying a location:

1. Will there be flammable gases or liquids stored, handled, or processed within or adjacent to the location?
2. What is the likelihood that a flammable concentration of gases or vapors will collect in the atmosphere of the location?
3. Once determined to be hazardous, how far could the hazard possibly extend?

In discussing flammable gas/air mixtures, a knowledge of vapor densities and liquid volatility is important. Vapor density indicates whether a gas is heavier or lighter than air. Lighter-than-air gases released in an open area will often dissipate rapidly because of their low relative density. Classification based on heavier-than-air flammable gases is normally conservative when compared to lighter-than-air gases or vapors.

The likelihood of a release of a sufficient quantity of flammable substances to form an explosive mixture depends upon the equipment, containers, and/or piping system containing the gas or liquids. If valves, compressors, pumps, or meters are present, they could leak. The likelihood also depends upon whether ventilation is available to dissipate the gas or vapors.

The extent of the hazardous area is determined by the presence of walls or barriers and air currents that may carry the gas or vapors away from the point of release.

3.7.3.4 Ventilation

For the purposes of area classification as outlined in this section, the definition of *adequate ventilation* is as follows:

a. *Open Structures.* An adequately-ventilated location is any building, room, or space that is substantially open and free from obstruction to the natural passage of air through it, vertically or horizontally. Such locations may be roofed over with no walls or may be closed on one side (Basis: NFPA 497).

b. *Enclosed/Partially Enclosed Structures.* Adequate ventilation, as defined in NFPA 30, is that which is sufficient to prevent accumulation of significant quantities of vapor-air mixtures in concentrations over one-fourth of the lower flammable limit (LFL).

3.7.4 Designing for Operational Safety

The following process controls and alarms are recommended for all vapor extraction and bioventing systems. At a minimum, the following process control components are required:

- Pressure/vacuum and flow indicators for each well, of the appropriate range for anticipated conditions
- Blower motor thermal overload protection
- Vacuum relief valve or vacuum switch to effect blower shutdown
- Sampling ports before and after air treatment and at each wellhead
- Pressure and temperature indicators, as well as flow control valves and pressure relief valves at blower inlet and outlet
- High level switch/alarm for condensate collection system
- Explosimeter — for sites with recently measured LEL levels greater than 10%

- For catalytic or thermal oxidizers:
    - automatic burner shutoff
    - temperature monitoring and control
    - interlock with vapor extraction control system
    - UL listed burners and fuel train.

3.7.5 Fire Protection

Fire detection and protection requirements will be dictated by local building and electrical codes and, if not otherwise stipulated by the NEC. The engineer must consider the need for, and appropriate placement and placarding of, fire extinguishers, smoke detectors, sprinkler systems (especially above or near activated carbon vessels), thermal overload switches for motors, and other alarms to minimize the risk of fire.

The engineer needs to delineate and classify each area within the equipment building or fenced compound according to NEC provisions.

Following are key topics that the electrical plan and specifications need to address:

- Fire detection
- A hydrocarbon gas detection system employing primary gas detectors calibrated for methane and supplemental detectors calibrated for propane and heavier gases
- A fire detection system employing thermal, ionization, and ultraviolet detectors
- Ventilation systems to maintain the specified number of air exchanges per hour to prevent buildup of explosive vapors
- Independently-controlled ventilation system and independently-controlled fire extinguishing system approved for the specific application. The fire extinguishing system should be designed to operate both automatically and manually
- All installations should comply with SAPC Design Guide Z501. Piping components that may eventually leak should not be installed above electrical equipment. Such components include screwed fittings (not seal welded), flanged joints, and any type of valve

- Some permanent vapor extraction treatment systems have sprinkler heads inside the carbon vessels for fire protection. A heat detector may be included to activate the fire suppression system. Otherwise, a fire department connection may be sufficient to allow spraying of water on the carbon

3.8 Drawing and Specification Development

The level of detail for design documentation for vapor extraction/ bioventing systems varies widely depending upon contractual arrangements, site size and complexity, and whether prefabricated systems are used. Given this wide range of variability, it is the responsibility of the engineer in responsible charge to ensure that safety and human health precautions are adequate and that remedial goals can be attained in a cost-efficient manner. In the past few years, package-type vapor extraction/bioventing systems have proliferated. The engineer must realize that the design criteria for a package or skid/containerized vapor extraction system may not be appropriate for a specific site. It is therefore imperative that the engineer gather and review the information and data in a set of drawings and specifications as described in this section.

A complete design package for a vapor extraction or bioventing system will consist of a drawing set, specifications, vendor cut sheets (for key pieces of equipment showing blower and/or pump curves), design calculations (head loss in piping, tank sizing, etc.), pilot test results, and documents describing current site conditions. An operation, maintenance, and monitoring plan may also be required. The following list of drawings is recommended for all such design projects:

1. *Site Plan* — shows current site conditions, property boundaries, ownership, buried utilities, structures, canopies, driveways, surface cover (e.g., concrete, gravel, or asphalt), and all existing structures. Existing and proposed piping and well locations must be clearly differentiated. A well schedule, listing all wells onsite, their current and proposed use, size, materials of

construction, depth, screened interval, etc. can eliminate confusion during construction and operation.

2. *Well and Piping Construction Details* — provides a detailed cross section of each well with materials and dimensions specified, well vault details, trench cross sections, piping connections, other yard details, fencing details, etc.
3. *Process and Instrumentation Diagram* — presents a schematic view of the entire process from the wells to the final treated system exhaust, including water collection, storage, treatment, and discharge; valves; instruments; electrical interlocks; alarms; and switches (level, pressure, vacuum, vacuum relief, etc.).
4. *Mechanical Details* — includes dimensional details of pipe manifolds, attachment of vacuum gauges and other instrumentation, valves, well vaults, monitoring points, and equipment.
5. *Electrical Plans* — detail the location of the power source, wiring routes, lighting, alarms, outlets, and heaters; and provides NEC classifications of each area of the equipment enclosure, ladder logic diagrams for PLC, control panel layout, motor control panel layout, existing and proposed electrical panels, etc.
6. *Building or Equipment Enclosure Plan and Equipment Layout Plans* — show excavation plan, footings, foundation details, slab details, slab drainage (sump) details, dimensions of building or enclosure, locations of each piece of equipment, electrical panels, penetrations (for containers, specify vendor-supplied or field-built), elevations of outside and inside equipment enclosure, exhaust stack location, pipe manifolds, interior walls, etc.

3.8.1 Purpose

Design drawings and specifications are necessary to communicate the layout, operation, and construction details to a number of people with a wide degree of knowledge and concerns about the proposed project. These documents provide the owner with the layout of the system so that local facility personnel can be prepared for the construction and operational procedures. The construction contractor needs enough detail to safely build the system as designed and estimate construction costs. For simple systems, sufficient specifications may be provided directly on the design drawings. However, a separate specifications document may be needed for more complex systems. This ensures that the engineer has considered and included all necessary components.

Standard specifications have been developed that may be applicable to a specific site or project. These sets of standard specifications have been created (and are updated periodically) by various trade and professional organizations and, in some cases, the federal government. Such specifications include:

1. Construction Specifications Institute — publishes standardized specifications for all construction trades.
2. Naval Facilities Engineering Command (NAVFAC) and National Defense Center for Environmental Excellence (NDCEE) Program — are developing criteria for the engineering design of remediation technologies.
3. National Institute of Building Sciences — publishes Construction Criteria Data Base.

Many times, a vapor extraction or bioventing construction project is divided into several tasks based on the various trades that will be necessary to complete the project. Similarly, specifications are often organized based on construction segment as indicated in the following sections.

3.8.2 Contractual, Financial, and Legal (Insurance) Requirements

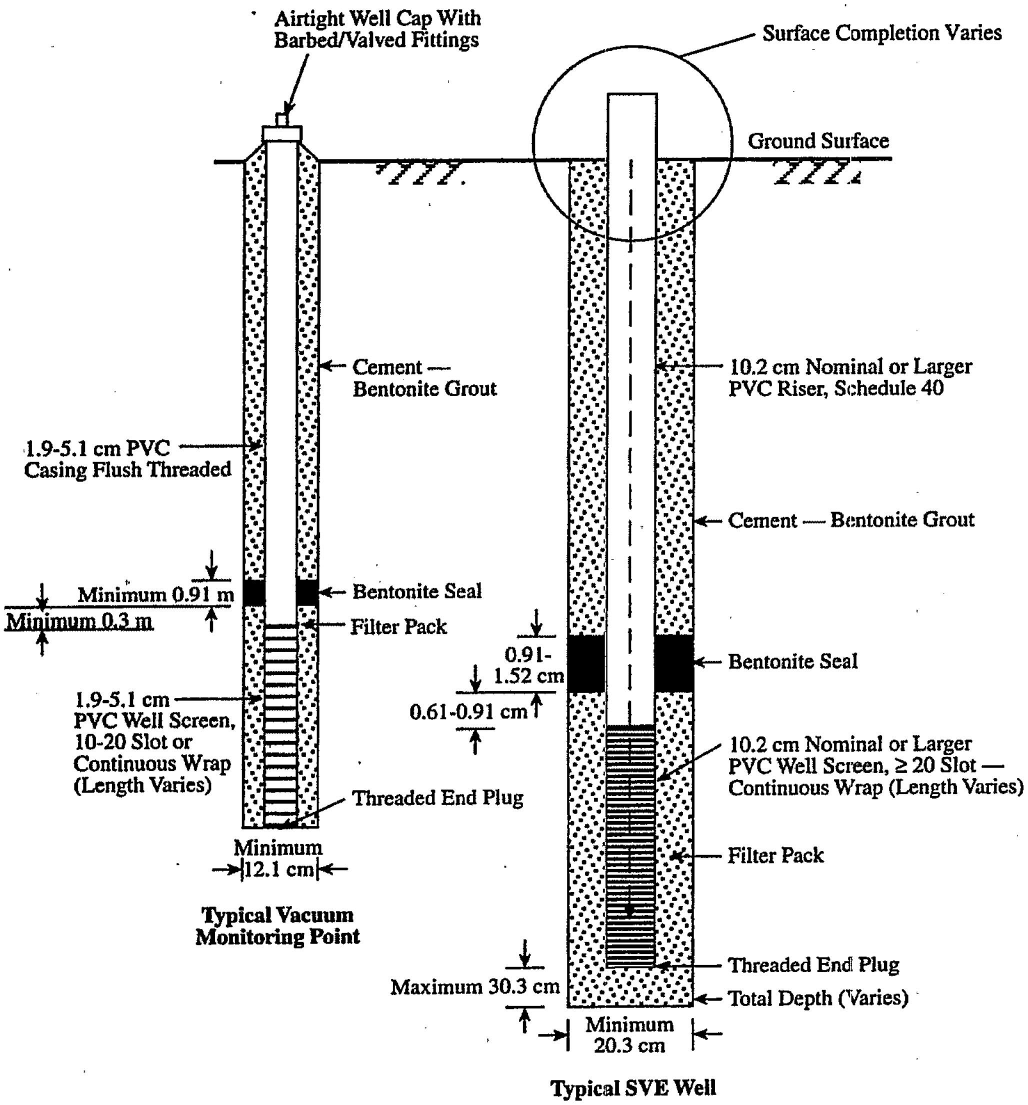
The design specifications also identify the owner of the facility being built, in other words, the party ultimately responsible for the health and welfare of the people working in or near the system. The specifications also must identify the engineer of record (who has supervised the design) and who will be responsible for the actual construction of the system.

3.8.3 Wells, Vaults, Piping, and Equipment

3.8.3.1 Vertical Extraction Wells (US ACE 1995)

Vertical extraction wells can be used for passive or active air injection, including bioventing vents (Figure 3.16).

Figure 3.16
Vertical Vapor Extraction Well/Monitoring Point Construction Details
(not to scale)



Source: US ACE 1995

1. ***Standards.*** Standards for the materials and installation of extraction wells have been developed by such organizations as the ASTM, the American Water Works Association (AWWA), the American National Standards Institute (ANSI), the National Sanitation Foundation (NSF), and US EPA. A listing of the pertinent standards is provided below:

Well Construction and Materials

ASTM	F 480	Thermoplastic Well Casing Pipe Couplings Made in Standard Dimension Ratios (SDR), Schedule 40/80, specification.
ASTM	D 1785	Specification for Polyvinyl Chloride (PVC) Plastic Pipe, Schedules 40, 80, and 120.
ASTM	D 2241	Specifications for PVC Pressure-Rated Pipe (SDR-Series).
ASTM	D 5092	Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers.
AWWA	A100	Water wells.
NSF	Standard 14	Plastics, Piping Components and Related Materials.
US EPA	570/9-75-001	Manual of Water Well Construction Practices.

Cement Specifications

ASTM	C 150	Specifications for Portland Cement. Soil Classification
ASTM	D 2487	Classification of Soils for Engineering Purposes.
ASTM	D 2488	Practice for Description and Identification of Soils (Visual-Manual Procedure).

2. *Materials.*

a. *Casings.* New PVC pipe, 100 to 150 mm (4 to 6 in.) in diameter, is normally used for vapor extraction well casing. A reference to ASTM D 1785 or ASTM F 480 is appropriate. Larger diameters are preferred to increase flow capacity, but require larger boreholes. Assess the vacuum drop inside the well casing and screen diameters based on the pneumatic analysis procedures used for piping. Casing and screen diameters of 100 mm (4 in.) are adequate for most applications unless the formation has a high air permeability, and individual well extraction rates are high (say 400 scfm or higher), in which case larger diameters may be appropriate. Other materials may be specified if contaminants, at expected concentrations, are likely to damage PVC. Materials with appropriate physical properties and chemical resistance may be used in place of PVC where economical. Heat-resistant materials should be used if thermal enhancements to vapor extraction are applied at the site. PVC casing exposed to sunlight should be protected or treated to withstand ultraviolet radiation without becoming brittle. The casing must be strong enough to resist collapse at the expected vacuum levels and grout pressures. The specifications should require casing with flush-threaded and O-ring seals. Table 3.7 indicates a range of acceptable sizes for extraction well materials including casing.

b. *Screen.* The well screen is usually PVC with slotted or continuous-wrap openings. Continuous-wrap screen is strongly preferred because the increased open area reduces the pressure drop across the screen and therefore reduces blower energy costs. Slot size is generally 0.5 mm (0.02 in.) but should be as large as possible to reduce the pressure/vacuum drop across the screen. Slot sizes of 1.01 mm (0.04 in.) or larger may be used. Larger slots sizes may, in a few cases, lead to increased entrainment of abrasive particles in the air flow. If the well will be used to recover groundwater or other liquids, the slot size must be chosen based on formation gradations. Screen with flush-threaded joints and O-ring seals is preferred.

Table 3.7
Extraction Well Materials

Components	Operating Size Range Metric	 English	Comments
Casting	50 mm 100 mm 150 mm	2 in. 4 in. 6 in.	Sch 40 Larger diameters should be used where vacuum losses inside well may be high
Screen	50 mm 100 mm 150 mm	2 in. 4 in. 6 in.	Sch 40 0.5 mm or larger slots
Filter Pack	$C_u \leq 2.5$		Refer to Section 3.8.3.1-(2)(c) Filter Pack
Piping	50 mm 100 mm 150 mm 200 mm	2 in. 4 in. 6 in. 8 in.	Sch 40
Valves (Ball)	50 mm 100 mm 150 mm 200 mm	2 in. 4 in. 6 in. 8 in.	Sch 40
Joints (Elbow)	50 mm 100 mm 150 mm 200 mm	2 in. 4 in. 6 in. 8 in.	Sch 40

Source: US ACE 1995

c. *Filter Pack.* Pack material should be a commercially available, higher uniform gradation of siliceous sand or gravel with no contaminants (chemical or physical). A uniformity coefficient (C_u) of 2.5 or less is recommended. The actual gradation should generally be based on the formation grain size and the screen slot size. Coarser material may be used; however, coarser gradations may, in a few cases, lead to increased entrainment of abrasive particles in the air flow. If the well is to be used to recover liquids as well as air, the filter pack must be sized appropriately.

d. *Seal and Grout.* A well seal is necessary to prevent entry of grout into the filter pack and well screen. Unamended sodium bentonite, as pellets, granules, or a high-solids bentonite grout, is normally specified for the seal material. The seal is placed above the water table and thus pellets and granules must be hydrated. A cement grout is preferred to fill the annulus above the seal to the ground surface because it resists desiccation cracking. The mixture of the grout should be specified and is normally one 42.6 kg (94 lb) bag of cement (optionally with up to 2.25 kg [5 lb] of bentonite powder to further resist cracking), with less than 18 L (4.75 gal) of clean water. Reference should be made to ASTM C 150 in the specifications as appropriate.

e. *End Caps and Centralizers.* Flush-threaded end caps, consistent with the casing and screen in size and material, should be specified. Centralizers center the well in the borehole and must be sized appropriately for the casing and borehole. Centralizers should be made of material that will not lead to galvanic corrosion of the casing. Stainless-steel centralizers are recommended with PVC or stainless-steel casings.

3. *Installation.*

a. *Drilling Methods.* There are many methods for drilling. Some methods would, however, be less desirable because of the potential to smear the borehole and plug the unsaturated soils. For example, use of drilling mud should be prohibited. Hollow-stem auger drilling is most common and is preferred.

b. *Soil Sampling and Logging.* Sampling of soils encountered during drilling increases understanding of the subsurface and allows better decisions to be made about well construction including screen placement. Sampling of soils at regular intervals, at least every 1.5 m (5 ft) is recommended; sometimes, continuous sampling is appropriate. Samples should be obtained by an appropriate method, such as split-spoon sampler or thin-walled tube according to ASTM D 1586 or D 1587, respectively. Sample volume requirements should be considered when specifying the sampling method. The sampling for chemical and physical analyses should be done according to an approved sampling and analysis plan. It is strongly recommended that a drilling log be prepared by a geologist or geotechnical engineer. Materials encountered should be described according to a standard such as ASTM D 2488. In particular, features relevant to air transmission, such as shrinkage cracks, root holes, thin sand layers, and moisture content should be identified.

c. *Borehole Diameter and Depth.* Normally, the diameter is at least 101 mm (4 in.) greater than the diameter of the casing and screen to allow placement of the filter pack. The depth of the borehole should be based on the screen depth. The borehole should only extend to 0.3 m (1 ft) below the projected bottom of the screen.

d. *Screen and Casing Placement.* Screen and casing should be joined by flush-threaded joints and suspended in the center of the borehole. Centralizers should be placed on the casing at regular intervals if the depth of the well exceeds some minimum value such as 6 m (20 ft).

e. *Filter Pack Placement.* The filter pack should be placed around the screen to some level above the top of the screen, normally about 1 m (3 ft). Filter pack is normally placed dry by pouring down a tremie pipe. The pipe is used to prevent bridging of grains in the annulus and is kept near the top of the pack material during placement. The pack material should be carefully stored and handled to avoid contamination from undesirable materials.

f. *Seal and Grout Placement.* The grouting of the well is critical to preventing short circuiting. Normally 1 to 2 m (3 to 6.5 ft) of a bentonite well seal are placed above the filter pack. The specification should include a requirement for hydrating the bentonite before placement of the grout. The specification should require the addition of a volume of distilled or potable water for every 150 mm (6 in.) lift of bentonite pellets or granules. The bentonite should hydrate for at least 1 to 2 hours before placing the grout. This can be avoided by using a bentonite high-solids grout as the seal. The high-solids bentonite grout should be placed by tremie pipe. Cement grout should also be pumped into the annular space via a side-discharge tremie pipe, and the pipe should be kept submerged in the grout during grout placement. If the grout is to be placed to a depth of less than 4.5 m (15 ft), the grout may be poured into place directly from the surface.

g. *Surface Completion.* The completion of the wellhead will depend on the other features of the design, such as the piping and instrumentation requirements. An appropriate "tee" may be placed below or at grade to establish a connection with buried or aboveground piping, respectively. A vertical extension from the tee to a specified level will allow attachment of appropriate instrumentation. If finished above grade, the well may require suitable protection, such as bollards, to avoid damage to the well from traffic, etc. A well vault may be required. If a surface cover is used, the cover must be sealed around the well. In colder climates, where frost is a factor, subsurface vaults and wellheads must be protected from freezing. For this purpose, electric heat tape is frequently used for wrapping pipes and fittings. In regions of extreme cold where electric heating is economically infeasible, extruded styrofoam insulation (which has a low moisture absorptivity) is placed over the vault. Frost will not readily penetrate directly below the insulation. Wellhead security is provided by installing vaults with padlocks. Aboveground wellheads can be enclosed within steel casings with steel caps, which can then be locked. In addition to sampling ports in the extraction manifold, ports should also be located on individual wellheads in order to differentiate between various extraction locations. Also, each wellhead should be fitted with both a vacuum gauge and a shutoff valve, and possibly, a flow-measuring device if individual wellhead flow rates are desired.

h. *Surveys.* The horizontal coordinates of each well should be established by survey. The elevation of the top of the casing, if the well intercepts groundwater, and the water elevation are of interest. The accuracy of the surveys depends on the project needs, but, generally, it should be to the nearest 0.3 m (1 ft) for the horizontal coordinates and the nearest 0.003 m (0.01 ft) for elevation.

i. *Dual Recovery.* If groundwater has been impacted, the same well may be used for vapor and groundwater extraction. The screened interval should intercept the groundwater zone as well as the contaminated vadose zone. Groundwater pumps can be installed to remove the impacted groundwater and also serve to depress the water table. This will counteract the tendency for groundwater to upwell and will expose more soil to air while a vacuum is being applied within the well.

3.8.3.2 Soil Gas/Vacuum Monitoring Points

This section provides guidance for design and specification of soil gas/vacuum monitoring points.

1. ***Materials.*** Generally, the same materials can be used for the monitoring points as for the extraction wells; however, there are differences in size.
   a. *Casing.* Generally, 20 to 50 mm (3/4 to 2 in.) diameter PVC pipe is used. Flush-threaded pipe is preferred, but for smaller diameters, couplings may be needed. Smaller diameter metallic or plastic rigid piping may also be used. Smaller diameters require less purging prior to sampling. Flexible tubing can be used as well, but it is not recommended for long-term use.
   b. *Screen.* Either slotted or continuous-wrap screen can be specified. Slotted pipe is adequate for monitoring ports. Continuous-wrap screen is not commonly available at the smaller diameters (less than nominal 50 mm [2 in.] diameter) but can be ordered. Slot sizes smaller than those typically used for extraction wells may be appropriate for monitoring points (i.e., 0.25 to 0.50 mm or 0.01 to 0.02 in. slots). Other "screen" types can be used. Options include

slotted drive points, porous points, or, for short-term use, even open-ended pipe.

c. *Filter Pack.* Filter pack material should be appropriately sized for the screen slot width. The pack simply provides support for the screen and is not critical to monitoring point function. In some cases, no filter pack will be necessary.

2. *Installation.*

a. *Drilling Methods.* Although a hollow-stem auger is still the primary means of installing monitoring points, direct-push methods can also be used to place slotted drive points or other vacuum/soil gas probes at specific depths. Again, mud or fluid-based drilling methods are not appropriate for this work.

b. *Soil Sampling and Logging.* As with vapor extraction/bioventing wells, it is appropriate to adequately sample the materials encountered for logging purposes and physical and chemical testing.

c. *Borehole Diameter and Depth.* The borehole diameter should be approximately 101 mm (4 in.) larger than the screen/casing to allow placement of the filter pack. This would not apply to points placed by direct-push methods. Adequate room for proper installation should be allowed if multiport monitoring systems are to be used. Multiport monitoring systems are difficult to place and it is often more time-efficient to drill separate holes for the points at different depths in a cluster. Monitoring point depth selection is entirely site dependent, but monitoring of multiple depths within the vadose zone is recommended. It may be appropriate to extend the monitoring point into the water table to monitor water table fluctuations due to seasonal change or in response to the vapor extraction/bioventing system or other remedial actions.

d. *Screen and Casing Placement.* Casing and screen is normally placed by methods similar to those used to install vapor extraction/bioventing extraction wells; however, direct-push techniques are alternatives for quickly placing monitoring points to the desired depths. The actual means of placement is dependent on the system, materials used, and site geology.

e. *Filter Pack, Seal, and Grout Placement.* The procedures for sealing the well would generally be the same as those used for vapor extraction/bioventing wells. Points placed by direct-push methods may depend on a tight seal with native soil to prevent leaks. Multiport monitoring systems require careful placement of seals between the monitored intervals to prevent “short-circuiting” between the various intervals.

f. *Surface Completion.* The monitoring points should be completed with a suitable barbed/valved sampling port or septum attached by threaded connection to an appropriate end cap. The cap should be attached to the top of the casing by an airtight connection. The points can be set above grade with suitable protection or below grade, typically in a flush-mount valve box.

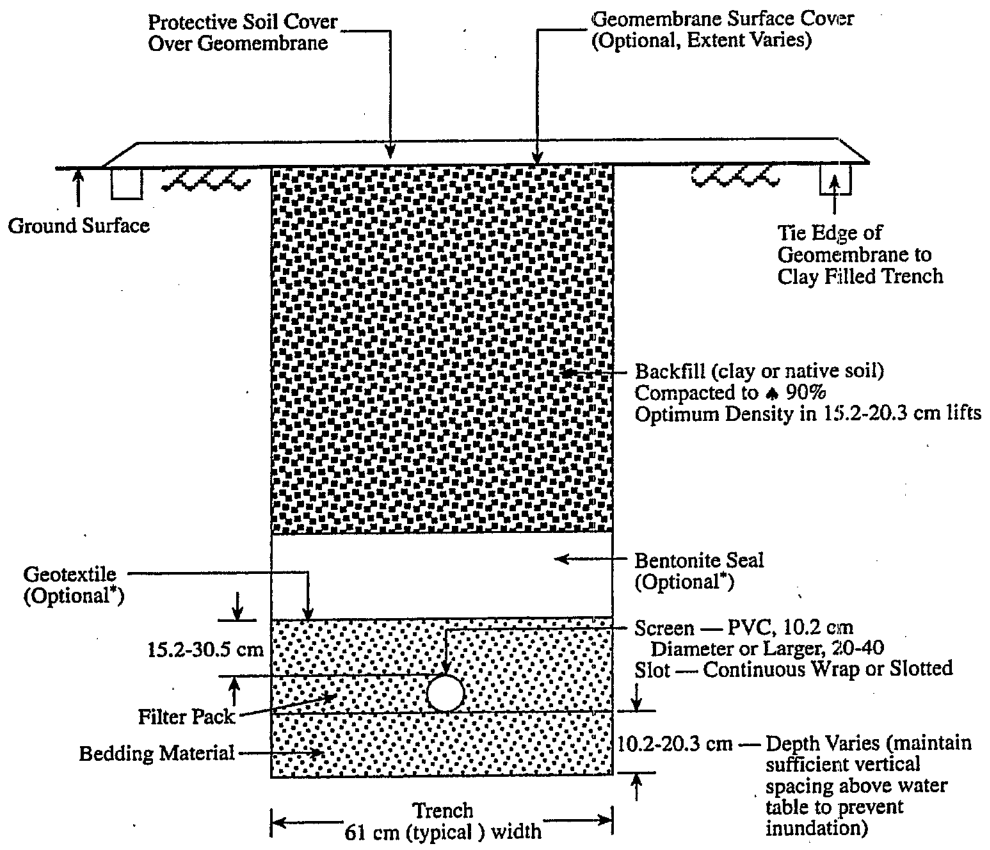
g. *Surveys.* Horizontal coordinates are necessary for each point, and vertical coordinates to the nearest 0.003 m (0.01 ft) are necessary if monitoring the water levels.

3.8.3.3 Vapor Extraction Trenches

Vapor extraction trenches are often used at sites with shallow groundwater or near-surface contamination; thus, the depth of excavation is often modest. Placement of multiple pipes in the same trench, each with a separate screen interval should be considered if selective extraction from various portions of the trench is required. The placement of a horizontal recovery system can be accomplished by several methods, including normal excavation, trenching machines (which excavate and place pipe and filter pack in one pass), and horizontal well drilling. Figure 3.17 illustrates a typical horizontal vent well design.

1. ***Materials.*** Materials specified for extraction trench construction are often similar to those specified for vertical wells. Different materials may be needed if specialized trenching (or drilling/jacking) methods or machines are used. Differences between horizontal and vertical applications are discussed below.

Figure 3.17
Typical Horizontal Vent Well Design



NOT TO SCALE

*Geotextile and bentonite seal may be replaced with geomembrane

Source: US ACE 1995

a. *Casing.* Although PVC casing is commonly used, flexible or rigid polyethylene pipe may be more efficient for certain excavation methods such as trenching machines. The pipe must resist the crushing pressures of the backfill and compaction equipment. Reference should be made to the where required. PVC pipe is not appropriate for uses involving high pressures (i.e., many atmospheres) because it cannot safely withstand the stresses that are imposed. However, since less than one atmosphere of vacuum or pressure should ever be exerted with vapor extraction/bioventing, PVC can be used provided there are appropriate pressure/vacuum relief valves. When using flexible hose lines on the vacuum side of the system, the engineer should be aware that vacuum limits may be far less than pressure limits.

2. *Temperature Limitations.* Plastic piping, such as PVC, chlorinated polyvinyl chloride (CPVC), polypropylene (PPE), or polyvinylidene fluoride (PVDF), is commonly used for vapor extraction/bioventing systems. Temperature limitations of the material must not be exceeded. Plastic piping should not be used on the blower discharge; if the blower overheats, the piping may melt.
3. *Insulation.* Insulation and heat tracing can be used to prevent unwanted condensation in the piping. High-temperature incinerator components should be installed to prevent burn hazards.
4. *Mechanical Stress.* Supports for all piping should have a nominal diameter of at least 5 cm (2 in.). The supports should be designed and spaced in accordance with ANSI/MSS SP-58, -69,-89, and -90.
5. *Pneumatics and Hydraulics.* The piping system must be sized to be compatible with the overall pneumatic scheme. In addition to considering frictional losses, it may be necessary to size the piping small enough to achieve sufficient velocity to prevent solids from settling. Velocities greater than 1.8 m (6 ft) per second are recommended for pumped condensate lines.
6. *Chemical Compatibility.* A list of acceptable materials is provided in Table 126.1 of ANSI B31.1. Specifically, chlorinated solvents may degrade plastic piping. Piping that will be exposed to sunlight must be UV resistant or have a UV-protective coating applied.
7. *Pipe Slope.* All piping should be sloped to promote drainage of condensate back toward the wellhead or to condensate collection points. Low spots are to be avoided in piping runs.

3.8.3.5 Valves

In vapor extraction/bioventing systems, valving is used for flow rate and on/off control. A typical system will have a flow control valve on each extraction or injection line.

1. The valves may be manually controlled or automatically actuated by an electric or pneumatic power source. Pneumatic actuators tend to be simpler and less costly than electric actuators, particularly for explosion-proof applications. However, if a pneumatic power source is not readily available, an air compressor must be procured, operated, and maintained. Since vapor extraction/bioventing systems do not typically have a large number of automated control valves and electric power is necessary for other components, electrically-actuated valves are frequently employed.
2. Most of the above considerations that apply to piping also apply to valves. The valves must be chemically compatible with the liquid or air stream; they must operate safely in the temperature and pressure range of the system; they must not create excessive frictional loss when fully opened; and in some situations, they must be insulated and/or heated to prevent condensation. Also, the operating range of a control valve must match the flow control requirements of the application.
3. The control valves must be properly sized. A flow control valve functions by creating a pressure drop from the valve inlet to outlet. If the valve is too large, the valve will operate mostly in the almost-closed position, giving poor sensitivity and control action. If the valve is sized too small, the upper range of the valve will limit flow. Formulas and sizing procedures vary with valve manufacturer. Computations typically involve calculating a capacity factor (C_v), which depends on the flow rate, specific gravity of the fluid, and pressure drop. The engineer calculates C_v at the maximum and minimum required flow rates. The calculated range of C_v values must fall within the range for the valve selected.
4. During the mechanical layout of the system, care needs to be taken to ensure that the valves are accessible. They should be numbered and tagged and referred to by number in the design and in the operation and maintenance manual.

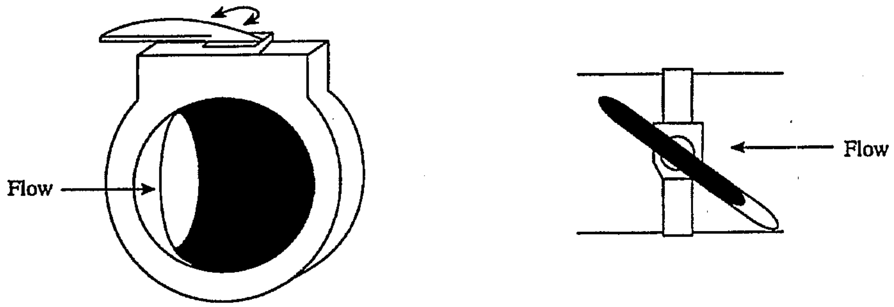
5. The following is a brief description of several valves commonly employed for vapor extraction/bioventing systems (Figure 3.18):
    a. *Ball Valve.* Used primarily for on/off control and some throttling applications, the ball valve uses a rotating ball with a hole through the center to control flow.
    b. *Butterfly Valve.* Used for both on/off and throttling applications, the butterfly valve controls flow with a rotating disk or vane. This valve has relatively low friction loss in the fully open position.
    c. *Diaphragm Valve.* A multiturn valve used to control flow in both clean and dirty services. The diaphragm valve controls flow with a flexible diaphragm attached to a compressor and valve stem.
    d. *Needle Valve.* A multiturn valve used for precise flow control applications in clean services, typically on smaller diameter piping. Needle valves have relatively high frictional losses in the fully open position.
    e. *Globe Valve.* Used for on/off service and clean throttling applications, this valve controls flow with a convex plug lowered onto a horizontal seat. Raising the plug off the seat allows for fluids to flow through.

3.8.3.6 Manifold Systems

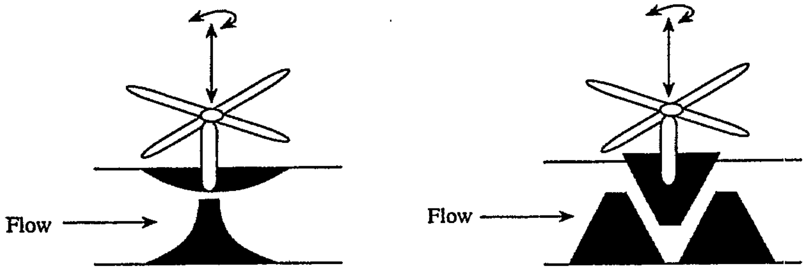
A manifold system interconnects the injection or extraction wells into a single flow network prior to being connected to the remainder of the vapor extraction/bioventing system (Figure 3.19). A manifold system will include a series of flow-control valves, pressure and air flow meters, and VOC sampling ports at each wellhead These devices may be grouped in one central location for convenience. The manifold system is typically constructed of PVC, high-density polyethylene (HDPE), or stainless steel.

The manifold system should have a manual air control valve to bleed fresh air into the vapor extraction/bioventing pump system or reduce vacuum levels and temperatures within the motor/blower. Air control valves control the applied vacuum in the subsurface and are used to start the vacuum system from a condition of zero applied vacuum. These valves should be of a

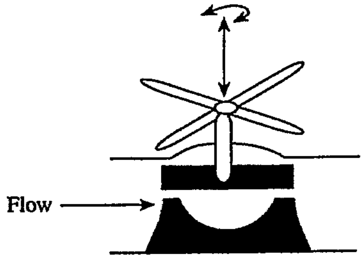
Figure 3.18
Valve Schematics



(a) Ball Valve **(b) Butterfly Valve**



(c) Diaphragm Valve **(d) Needle Valve**



(e) Globe Valve

Source: US ACE 1995

performance curves, and design vacuum or pressure and flow rate. Key pieces of equipment include blowers, vacuum pumps, water pumps, air filters, control or automatic valves, pressure/vacuum relief valves, silencers, air and water treatment equipment, and condensate accumulation tanks.

For dual-phase systems, the pump vacuum curve and temperature curve are critical in planning for adequate seal water flow to prevent overheating.

3.8.5 Electrical

The design of any vapor extraction or bioventing system must comply with local, state and national electrical codes. Most important in designing a system is the compatibility of the equipment with a potentially explosive atmosphere created from extracting VOCs from soil as described in Section 3.7.3.

3.8.6 Equipment Buildings and Enclosures

Specifications for buildings must include excavation sequence; fate of all removed materials; responsibility for management of removed materials; concrete specifications; and foundation and footing design loadings for wind, snow, weight of equipment or vehicles inside building, etc. Equipment enclosure specifications need to address weight, dimensions, loading lugs, structural anchoring, penetrations (vendor-supplied or field-built), size of all openings, locking mechanisms, ventilation openings and blowers (if package unit), electrical requirements, and controls provided.

3.9 Cost Estimating

This section discusses considerations in estimating costs of vapor extraction/bioventing systems. The strategy and general approach to cost estimating for vapor extraction/bioventing remediation are presented below (US ACE 1995).

3.9.1 Cost Estimating

The four basic levels of cost estimates that can be developed for environmental remediation projects, from least accurate to most accurate, are: (1) planning, (2) feasibility, (3) preliminary, and (4) detailed. These four estimates are normally completed in sequence as a remediation project progresses. The level of detail, accuracy, and reliability of the cost estimate increases as the project life cycle increases from the planning stage to the design stage. The time and effort to prepare each level of cost estimate also increases with the level of accuracy desired.

As shown in Table 3.8, the nomenclature for these four remediation cost estimates parallels the construction and waste management operations industries. For instance, the detail and reliability of the remediation planning estimate is roughly equivalent to that of a magnitude estimate in waste management operations. Similarly, a remediation feasibility cost estimate is similar to a budget estimate in the construction field.

Table 3.8
Types of Cost Estimates

Level of detail, accuracy, and reliability increases ↓

Construction	Environmental Remediation	Waste Management Operations
Planning/Feasibility Study	Planning	Magnitude
Budget/Conceptual Design	Feasibility	Preliminary
Preliminary Design	Preliminary	Performance
Detailed Design	Detailed	

Source: DOE 1994

Table 3.9 summarizes the level of accuracy associated with each of the four basic forms of environmental remediation cost estimates. The planning estimate is often completed when there are a large number of unknowns and, therefore, has a relatively low accuracy ranging from -50% to +100%. In contrast, a detailed estimate is completed once the complete scope of the remediation work has been identified and the remediation details and complexities are well known and quantified. A detailed estimate provides a much higher degree of accuracy, normally within +/-25%. Along with each of these cost estimates, the engineer must document assumptions used in preparing the estimate, include an assessment of the accuracy of the costs, and provide a statement of limitations.

Table 3.9
Environmental Remediation Estimates: Characteristics

Level of detail, accuracy, and reliability increases

Type	Accuracy	Characteristics
Planning	-50% to +100%	• Large amount of unknowns • Analogy or parametic method typically used
Feasibility	-30% to +80%	• Low level of detail • Takeoffs as basis
Preliminary	-30% to +70%	• After preliminary assessment is complete • Site inspection complete • Unit costs applied to some categories
Detailed	+/-25%	• Final estimate for assessment and cleanup phase • All scoping complete • Details/complexities well known

Source: DOE 1994

3.9.2 Cost Estimating Procedures

The following steps are typically followed when estimating costs.

Step 1. Separate Estimate into Categories. Categories of costs in estimates include site work, capital, nonconstruction, operation, maintenance, and shutdown costs. Proper categorization is essential when using cost ratios; for example, process equipment replacement is often estimated as a percentage of capital equipment costs, particularly in early stage cost estimates. The capital equipment cost should not include items such as earthwork that require little or no equipment replacement.

Step 2. List Cost Components. A list of cost components is prepared for each category. Components common to vapor extraction/bioventing remediation are discussed throughout this manual and are listed in Section 3.9.4.

Step 3. Obtain Cost Information. Cost information can be obtained from various cost data sources, including vendor quotes, cost estimating manuals, previous remediation projects, and literature searches. Experienced cost engineers maintain files on former price quotes for common components. Whenever possible, prices should be obtained from several sources. The engineer must be aware of exactly what is included in unit prices and document this information in the estimate.

Step 4. Analyze Cost Data. Cost information is often used to decide among remediation alternatives. It is also used to make financial decisions such as whether to lease or purchase equipment. The goal of the estimate affects the method and level of detail of analysis. A detailed discussion of finance is beyond the scope of this monograph; however, the engineer should be familiar with the following terms and concepts:

- net present worth analysis,
- rate of return method,
- capitalized cost method, and
- depreciation methods.

These financial analysis tools should be used for appropriate decision making. More detailed financial and economic considerations, such as taxes, future interest rates, and future inflation rates, are typically not considered in engineering cost estimates for analysis of remediation alternatives.

Step 5. Prepare Assumptions and Limitations. Often, the assumptions and limitations are as important as the estimate itself. Examples of limitations include:

- estimates based on limited data, such as limited characterization or design information;
- assumptions regarding the means and method of construction have been made;

- price fluctuation for materials and labor; and
- unpredictable regulatory decisions.

A typical list of assumptions will contain information regarding analysis of site conditions, quantities, project duration, and equipment. Sources of cost information, such as vendors and cost guides, should be referenced.

3.9.3 Cost Estimating Approaches

The cost engineer must ensure that costs are based on the appropriate operating vapor extraction/bioventing system. Operating costs can vary depending on the type and/or configuration of the system. Likewise, the operating approach to remediation can change the operating cost. If cleanup is scheduled for a shorter period of time, the system may be larger, with a higher cost. If cleanup is allowed to take longer, a smaller system that may operate more efficiently could be used.

3.9.4 Cost Estimating Checklist

A suggested cost estimating checklist is provided below (US ACE 1995). This list includes most major vapor extraction system cost components and has been divided into the following six categories: (1) pilot studies, (2) site work, (3) treatment system capital components, (4) nonconstruction, (5) annual operation and maintenance, and (6) shutdown. This is a typical list of cost components for preparing cost estimates for a feasibility study. Estimates for later design stages would likely be more detailed.

Pilot Studies

- Equipment rental or lease
- Equipment purchase
- Equipment assembly
- Extraction well and piezometer installation
  - Drilling
  - Materials
  - Supervision
- Impermeable liner construction
  - Materials

  - Labor
  - Construction equipment and operator
- Mobilization and transportation of equipment
- On-site labor to conduct the pilot study
- Laboratory analysis
- Data validation and interpretation
- Report writing
  - Quality assurance project plan
  - Health and safety plan
  - Contingency plan
  - Air monitoring plan
  - Groundwater monitoring plan

Site Work

- SVE/bioventing well and piezometer installation
  - Drilling
  - Materials
- SVE/bioventing trench installation
  - Earthmoving equipment and operator
  - Sand, gravel, and clean fill
  - Geotextile fabric
  - Soil disposal
- Site cleaning
- Foundation or pad
- Manholes
- Belowground piping
- Belowground electrical
- Surface cover
- Building construction

3.10 Design Validation

Design validation refers to the ongoing process of checks and improvements that are carried out in the planning, design, construction, startup, and operational phases. There is inherent uncertainty associated with any subsurface design since engineers must interpolate and extrapolate subsurface site conditions from a very small percentage of the soil actually observed and tested during a typical site investigation. The uncertainty for vapor extraction design is compounded because small changes in soil permeability can dramatically affect system performance. While engineers cannot overcome the uncertainty, they can incorporate contingencies into the design and implementation process.

During the conceptual design phase, engineers need to ask what may go wrong and how site conditions may vary from assumed conditions. During the preliminary design phase, engineers should develop strategies for assessing changing geologic or contaminant distribution conditions. These strategies may include layout of the monitoring system (piezometers, monitoring wells, offgas monitoring points) and system flexibility (additional smaller blowers instead of fewer larger ones, expandable manifolds, easily changeable offgas treatment options, extra pipes in trenches, etc.). Decision trees should be developed during the preliminary design phase to show how system layout or operating parameters can be varied for changing site conditions or if cleanup criteria are not met at compliance points.

During construction, further site knowledge is typically gained through the installation of additional wells or excavations. Processes need to be in place enabling (1) additional site information to be collected during construction by the field staff and (2) the engineers to capture that knowledge and make field changes as needed. For instance, the depth of contamination may be deeper than first estimated and so the depth of the vapor extraction wells would need to be modified. Finally, during system operation, the monitoring plans need to be implemented based on observed operating data, with changes in layout or operation as appropriate.

3.11 Permitting Requirements

3.11.1 Air Permit Requirements

Most vapor extraction/bioventing systems that discharge contaminants to the air need an air discharge permit or at least a formal variance from the air discharge permit requirements. The Clean Air Act, with associated amendments, provides the overall framework for U.S. air regulations. The Clean Air Act is the basis for National Ambient Air Quality Standards (NAAQS) and delineation of nonattainment zones where the NAAQS are not being met. However, at a practical level for vapor extraction/bioventing implementation, air discharges are regulated at the state level. State laws vary greatly concerning when permits are required, how they need to be obtained, and type of compliance monitoring required. Some states may require a formal air discharge permit for a system, while others may require only a formal registration of discharge if the discharge levels are below certain thresholds. A number of states also have streamlined processes for obtaining air discharge permits in conjunction with soil and groundwater remedial activities and do not require a permit if the engineer agrees to use some type of standard offgas treatment device (vapor-phase carbon, thermal treatment). Other states have permit exemptions for limited-duration pilot tests. Finally, counties or regions within states may also have regulations governing the type of treatment required, particularly, if such areas happen to be NAAQS nonattainment areas.

Although states vary as to when permits are required, information commonly requested in permit applications is described below. Generally, engineers have most of this information by the time a design is complete.

- *Application Forms.* Basic information on the site address, permittee information, and dates of installation and operation.
- *Process Information.* Discussion and depiction of the system process, including the offgas treatment system. A piping and instrumentation diagram and mechanical drawings are often sufficient.
- *Regulatory Discussion.* Summary of statutes and regulations under which the process is to be regulated.

- *Control Technology Analysis.* Description of how the offgas control device will control contaminants, if required.
- *Emission Summary.* Summary of the expected contaminants and actual and potential emission rates. Actual and potential emission rates can be difficult to predict if a pilot test has not been completed. In these cases, the engineer may need to estimate rates based on the approximate amount of contaminated mass in the soil and provide some basic site characterization information. Material safety data sheets may be required for each contaminant.
- *Stack Parameters.* Discussion of the discharge location and height. Catalog cuts of the treatment system can provide this information. The discharge flow rate, temperature, and gas sampling locations may also be required.
- *Site Information.* U.S. Geological Survey (U.S.G.S) map showing the site and a site plan showing discharge location, property boundaries, and surrounding off-site buildings and land use.
- *Operation and Maintenance Information.* Discussion of how the system is to be operated and maintained.
- *Receptor Information.* Names, addresses, and phone numbers of adjacent property owners/residents may be required.

Also, some states will require that this information be submitted by a professional engineer licensed in the state.

Compliance monitoring requirements for air discharge permits also vary widely among states. Most states require laboratory analysis of offgas concentrations at some specified interval (monthly or quarterly). A common offgas sampling technique is use of SUMMA canisters — evacuated canisters supplied by a laboratory with one atmosphere of vacuum in the canister. The vacuum in the canister enables the canister to withdraw its own sample when the sampling valve is opened. The valve can be adjusted to collect either an instantaneous or time-weighted sample for analysis. The analysis can be a TO-12 method, which analyzes non-methane hydrocarbons to a 1-ppb detection limit, or a TO-14 analysis, which measures individual VOC concentrations to a 0.1- to 0.5-ppb detection limit. Other common sampling methods include TO-1 and TO-2. In either method, an air sampling pump is used to draw a predetermined volume of air across an absorbent cartridge

(Tenax for TO-1 and Carbon Molecular Sieve for TO-2). US EPA Method 18 can also be used.

For thermal treatment systems, states may also specify process controls as part of compliance. For example, a specific residence time and combustion temperature may be required with routine monitoring of these parameters.

3.11.2 Surface Water Discharge Permit Requirements

Vapor extraction/bioventing systems may generate up to thousands of gallons of wastewater per day. Generation rates depend on the soil geology and whether active soil water removal is an intentional part of remediation or an unintended byproduct of soil vapor extraction. For systems generating little water (tens of gallons per day), the simplest method of water disposal may be containerization followed by batch discharge into a private or publicly-owned wastewater treatment plant. In such cases, appropriate authorizations are required from the owners/operators of the treatment systems. In cases where hundreds to thousands of gallons of water per day are being generated, the engineer needs to include a continuous method of water disposal. Unless the water can be continuously discharged to a private wastewater treatment plant, the two common discharge options are discharge to a surface water body or discharge to a publicly-owned treatment works (POTW).

The Clean Water Act established a national permit system for wastewater discharges directly to surface water bodies or indirectly into surface water bodies via a POTW. Direct discharges to surface water bodies are regulated by Section 402 of the Clean Water Act, which established the National Pollutant Discharge Elimination System (NPDES). NPDES permits are administered by US EPA or authorized states. In general, an NPDES permit will:

- provide effluent limitations;
- establish monitoring and reporting requirements;
- establish a compliance schedule; and
- provide other general conditions.

Effluent limits may be based on water quality criteria, which consider the specific discharge characteristics (flow and quality of discharge, discharge loading rates, receiving stream flow and quality). The intent is to maintain national water quality criteria within the receiving stream. Effluent limits may also be based on technology considerations, such as what limits a liquid-phase carbon or air stripping treatment technology should achieve. Some states will grant general wastewater treatment permits for discharges of groundwater that have been contaminated with only petroleum products and are being treated with a multi-stage liquid phase carbon treatment system. The presumption is that the discharge levels of petroleum hydrocarbons will be below normal analytical detection limits.

Monitoring and reporting requirements will determine the frequency and type of sampling. For example, weekly sampling during the first several weeks of discharge may be required, with a shift to monthly effluent sampling after system performance has been established. Monthly discharge monitoring reports on the results of effluent sampling generally must be submitted to the regulatory agency.

General conditions of the permit may establish other criteria. For example, periodic inspections of the outfall may be required. Some states may require that the system be maintained by an operator with certification for the specific treatment technologies being employed at the site. In addition, the state's prerogative regarding site access, re-opening the permit, requirements for other submittals, such as operation and maintenance plans, and sampling and record keeping requirements are in the general conditions of the permit.

To obtain an NPDES permit, the engineer needs to submit to the primary regulatory agency (state or US EPA) the following information:

- information on the owner of the facility and site location;
- a description of the process, including any water treatment processes;
- a site location map (USGS) and site plan;
- information on the flow rates, contaminant concentrations, and receiving water; and
- names and addresses of surrounding property owners/residents.

3.11.3 Discharge Requirements to a POTW

The Clean Water Act also requires that POTWs establish their own pretreatment requirements for discharge into the wastewater treatment plant. Most of these pretreatment standards apply to specific industrial activities. However, some pretreatment standards apply to the discharge of groundwater, and are based on the discretion of the local POTW ordinances. Pretreatment standards are designed to protect against the generation of unsafe vapors in sewers or wastewater treatment plants, protect the basic treatment processes employed by the plant, and help ensure that the plants, in turn, do not generate sludges or other wastes that cannot be disposed. Pretreatment requirements may vary widely depending on the size and type of POTW. In addition, depending on the POTW design capacity, some discourage the discharge of groundwater into sanitary sewers. If they do accept the discharge, discharge costs may be in the range of $1 to $2 per thousand gallons, which can add considerable operational cost to a system.

Monitoring parameters for discharges typically include total organics, specific organic contaminants found at the site, some metals (depending on the plant), total suspended solids, pH, and flow. Monthly reports with analytical results may also be required.

3.12 Design Checklist

This section summarizes the activities and considerations discussed in this chapter in checklist form. While not all activities may relate to a particular project, the checklist should provide the engineer with an overall list of concerns/activities that should be considered.

Site Investigation/Regulatory Review

- Develop target zones from site investigation report
- Construct cross-sections from soil borings showing target cleanup zones
- Develop list of potential environmental permits
- Develop preliminary soil cleanup concentrations
- Determine list of chemicals of concern

Design Planning

- Develop overall design objectives, including desired time frame for remediation

- Complete conceptual design of treatment system on-site cross-sections and plan views
- Estimate contaminant mass to be removed/contained
- Identify need for pilot testing based on size and complexity of site
- Identify pilot test data objectives
- Assess need for pilot test and full-scale offgas treatment
- Identify other factors that will affect design, such as space, proximity to electrical power source, noise, facility operations, property, and access constraints
- Determine how the system will be built and relationship between desinger/contractor/operator

Preliminary Design

- Complete pilot test work plan
- Undertake pilot test
- Interpret pilot test results in terms of initial conceptual design; modify conceptual approach as required
- Complete air flow modeling as appropriate to design the rest of the treatment system (injection/extraction wells)
- Layout aboveground aspects of system — piping runs, equipment locations, discharge points
- Estimate total flow and mass removal rate; determine need for offgas treatment
- Evaluate and select appropriate offgas treatment technology
- Begin application for air and water discharge permits
- Develop a listing of major equipment items and preliminary sizing of those items
- Complete a piping and instrumentation diagram showing controls and interconnects
- Consider future modifications that may be required for the system

- Determine how discharge compliance and eventual soil cleanup will be demonstrated
- Determine electrical classifications
- Determine how subsurface air flow will be assessed during full-scale operations

Final Design Activities

- Complete analysis of system vacuum/pressure requirements with head loss assumptions
- Finalize sizes of blower(s) and other major equipment
- Complete civil construction details and specifications (well, trench, building foundation details)
- Complete final electrical and instrumentation and control drawings and specifications
- Complete final architectural drawings for buildings
- Develop construction quality assurance plan, including system functional and performance testing
- Develop a start-up plan, including samples to be collected and analyzed
- Develop an operations and maintenance plan for long-term system operation, including contingency plan for system modifications as required, reporting requirements, safety, compliance
- Develop a construction and operation safety plan
- Develop a final cost estimate for construction and operation
- Obtain final air and water discharge permits

4

IMPLEMENTATION AND OPERATION OF VAPOR EXTRACTION

The initial phases of implementation include development of a procurement strategy and contract negotiation. Later phases include design, construction, startup, operation, and monitoring of the vapor extraction system. This chapter discusses these basic project components in the sequence in which they generally occur.

4.1 Implementation

The key initial activities include identifying the resources needed to implement the technology, the contracting strategies to be used to secure the resources, and the form(s) of contracts to be employed. Resources typically required include engineers and a variety of construction contractors within multiple specialty and trade disciplines. More information is presented below on the preferred procurement strategies and contracting methods, especially as they relate to the role of the engineer. Also provided in this section is a brief overview of the construction of a typical vapor extraction system and the more common specialty construction disciplines that may be required to install and operate it.

4.1.1 Contracting Strategies

Two common approaches used to contract the resources to install vapor extraction systems are (1) the design-build or "turnkey" approach in which a single contractor designs, builds, constructs (and possibly operates, under a separate contract) the system; and (2) the conventional phased, design-bid-construct-operate approach which can involve multiple contractors and engineering firms (Fulton 1995). During the 1980s and early 1990s when fewer vendors had experience with vapor extraction, designing and installing such systems typically followed the conventional phased, design-bid-construct-operate approach. More recently, with the dramatic increase in the number of engineering and construction firms with direct experience with the technology, there is a growing interest in and use of the turnkey implementation philosophy and process (Schriener 1995).

Turnkey contractors are generally selected based upon bids received in response to the owner's preliminary design and performance specifications package. The turnkey team that is awarded the project is subsequently responsible for final design, construction, startup and, potentially, operation of the vapor extraction system. The level of system design and specification does not need to be nearly as detailed when using the turnkey approach where a single entity is responsible for both design and construction as compared to that required using the phased implementation approach. In fact, the design and construction specifications for turnkey projects can almost be entirely performance-based.

The continuity provided by this contracting strategy can also optimize project efficiency largely due to the construction manager's involvement in the project from the start through construction. The other key advantages of the turnkey approach are that it often shortens the project schedule and thereby possibly decreases overall project costs. The turnkey approach can help transfer many of the project risks and much of the management responsibility from the owner to the engineer/builder. This is, in part, due to the establishment of a single contract entity responsible to the owner for all aspects of design, construction, installation, and potential operation. In essence, this approach helps relieve the owner of many of the management, coordination, and systems integration activities that are otherwise required under the traditional phased approach with multiple contracts. Because the turnkey approach fosters closer coordination between the engineer and builder, the potential for disputes and change orders is reduced.

While the turnkey approach appears to offer substantial benefits, it does have certain disadvantages. The major one being that the owner has less direct control over the design.

Regardless of which approach is used, a strategy to screen, select, negotiate, and procure the necessary engineering and construction resources should be developed. The types of contracts used are discussed in detail in the following section.

4.1.2 Contracts

Firms hired to implement vapor extraction systems typically enter into one or a combination of four basic types of legal contracts with the buyer of the services. These forms of contracts include:

- lump sum, in which a single payment is provided for the defined scope of work;
- cost-plus-fixed fee, in which the direct costs of the services provided are reimbursed and an agreed-upon fee is paid for completion of the work;
- unit price, in which compensation is based upon agreed-upon unit costs and the number of units provided;
- time-and-materials, in which compensation is provided based upon agreed-upon labor rates, the estimated maximum number of man-hours worked, an project expenses incurred, agreed-upon handling charges for subcontractors and other direct costs; and
- some combination of various components of one or more of the four contract forms.

The four contracting options offer a range of tradeoffs between potential risks and rewards to the seller and the buyer. A buyer generally decides which type of contract will be employed to govern the installation of the vapor extraction system and selects the form of contract that provides the balance of risks and rewards consistent with the project objectives. Normally, the seller is only in a position to either accept or reject the terms. However, in many circumstances, particularly during the final stages of procurement, the seller may be successful in proposing an alternate form of contract that is attractive to both parties in order to close the deal. For example, a project may be bid as a time-and-materials, not-to-exceed contract. During contract negotiations, however, a contractor may offer to perform the work under a lump-sum arrangement that minimizes the financial risk to the buyer of the services while increasing the potential reward to the contractor.

Theoretically, the design and specifications for the vapor extraction system to be constructed should be sufficiently comprehensive to ensure that the work would be completed at roughly equivalent costs regardless of the form of contract employed. However, in reality, as discussed below, the inherent characteristics of each of the four types of contracts can influence the quality, schedule, and cost of a vapor extraction system installation. This is particularly true when the installation specifications are more performance-based than design-based.

4.1.2.1 Lump-Sum

Lump-sum contracts are typically employed when the plans and specifications for the installation work are sufficiently detailed to allow the prospective construction firms to precisely project the manpower and materials required to complete the job. A lump-sum contract requires that, upon satisfactory completion of an identified scope of work, the contractor be compensated for the fixed dollar amount identified in the contract. The contractor is awarded the fixed dollar amount regardless of whether more or less money is expended than originally budgeted for construction. However, the contractor may be given less than the fixed dollar amount if any set-offs, liquidated damages, or other penalties are provided for in the contract documents and assessed. Conversely, the contractor may be awarded more than the fixed dollar amount if owner-approved work is completed that was not included in the original scope of work for the lump-sum contract. The contractor may also be compensated for more than the lump-sum figure if the contract contains a financial incentive clause that rewards the contractor for successful performance.

Lump-sum contracts generally present both a greater financial risk and potential reward to construction contractors compared with other forms of contracts. The contractors have little recourse for recovery of funds if their budget estimate is too low or if they forget to include some element of work. The many unknowns involved with working in the subsurface during the installation of a vapor extraction system make this type of contract even riskier to the contractor. For example, a contractor may develop a lump-sum cost estimate assuming that the pipe trench excavations would proceed relatively quickly through the near-surface soils. However, in reality, the trenching may take twice as long due to the presence of unanticipated boulders, inclement weather, or other variables not addressed in the contract terms and conditions.

As a result of the high level of risk to the contractor associated with this type of contract, risks are typically addressed through contingency factors added into the project budget. If the work proceeds better than anticipated, the contractor may benefit by avoiding use of the built-in contingency fund.

While this may result in an inflated price for the work, the owner benefits from the profit considerations motivating the contractor to complete the work in the least practicable time.

4.1.2.2 Cost-Plus-Fixed-Fee

The cost-plus-fixed-fee contract is typically employed where the precise scope of work has yet to be defined. Such could be the case if the vapor extraction system needs to be installed in an emergency situation and prior to completion of a formal design. Another example where a cost-plus-fixed-fee contract may be appropriate is where an experimental variation of vapor extraction is to be applied and many unknowns are associated with construction activities. Finally, this contract vehicle may be appropriate if the vapor extraction system is to be constructed in a relatively inaccessible area, and the costs for conducting work in such areas are unknown.

Under the terms of a cost-plus-fixed-fee contract, the owner agrees to reimburse the contractor for all costs associated with the installation work and to pay the contractor an agreed-upon fee for the work. However, the fixed fee afforded to the contractor often does not increase even if the original work scope is expanded. With this form of contract, the owner assumes a greater degree of financial risk because no limits on costs are set. In addition, all scope changes and unknowns are the responsibility of the owner. Conversely, the contractor has no risk and little incentive to complete the installation work in a timely manner or at least cost. However, the contractor may provide a lower bid with this form of contract due to the reduced risk.

4.1.2.3 Unit Price

A unit-price contract may be used to facilitate construction if the volume of work cannot be established in advance of construction and where large quantities of few types of construction are involved. Under a unit-price contract, the contractor is compensated at an agreed-upon unit price for the number of specific units delivered. The agreed-upon unit costs include all of the contractor's labor, equipment, material, subcontractor, and overhead costs as well as desired profit. Examples of construction tasks associated with a vapor extraction system installation that could be included in a unit-price contracts include vapor extraction wells ($/liner foot), trenching ($/linear foot), piping ($/linear foot), soil disposal ($/ton), paving ($/square foot), and saw cutting ($/linear foot).

The principal advantage to the buyer in a unit-price contract is an increased ability to control and forecast costs. This is due in part because the number of variables that define the total project cost reduces to one: the number of units required to complete the work. While unit costs may simplify project cost controls, without a contract ceiling, the financial risk lies mainly with the owner.

The unit-cost contract also inherently provides financial incentive to the contractor to complete the work as quickly and efficiently as possible. However, the contractor does not have any incentive to find ways to use fewer units during construction.

Because the volume of work associated with the installation of vapor extraction systems can generally be well defined and because certain elements of the installation do not lend themselves to the unit-price concept (e.g., the purchase and installation of extraction blowers, instrumentation, controls, and treatment equipment), the unit-price contract is rarely used by itself in contracts for these installations. Unit costs are, however, frequently and effectively incorporated into lump-sum contracts for vapor extraction construction work. In such a contract, the installation of the extraction and treatment equipment inside an equipment building may be covered under the lump-sum portion of the contract, while well installation, trenching, and piping is addressed by unit costs.

4.1.2.4 Time and Materials

Similar to a cost-plus-fixed-fee contract, a time-and-materials contract may be employed to govern the installation of a vapor extraction system if the precise scope of work is poorly defined. Under a time-and-materials contract, the contractor is compensated for the labor hours expended, the materials used, and the subcontractors employed to accomplish a scope of work. Agreed-upon labor rates and handling charges for subcontractors and other direct costs are employed to determine the compensation due the contractor.

Time-and-materials contracting is often employed where implementation of vapor extraction is being completed using the turnkey approach. For example, an architectural/engineering firm may be hired on a time-and-materials basis to design and manage the construction, startup, and operation of a vapor extraction system.

The advantage of this form of contracting to the buyer and the supplier of the services is the relative flexibility in modifying the scope of work to be performed. Generally, this form of contract does put the buyer of the services at greater financial risk; however, the contract typically includes a not-to-exceed stipulation that is specifically intended to reduce this risk. The not-to-exceed condition in time-and-materials contracts can also provide incentive to the contractor to complete the work in a timely manner.

4.1.3 Role of the Engineer

The level of engineering needed to install and operate a vapor extraction system can vary significantly, depending on the construction approach taken (i.e., turnkey or design-bid-construct-operate). Typically, the engineer's involvement is greatest with the turnkey approach where the engineer is normally involved with the project from design through construction and operation. In contrast, where the conventional phased implementation strategy is employed, the engineer may be involved with only select project phases. For example, in cases where the system is designed by the owner, the engineer may only be hired specifically for construction management.

The possible extent of engineering involvement in a turnkey project is discussed in this section. Given that engineers can also be retained under the conventional phased scenario to perform one or more of these services, emphasis has been placed on four of these component engineering roles, namely, design engineer, construction manager, construction overseer, and operator.

4.1.3.1 Design Engineer

The design engineer is typically tasked with taking the preliminary vapor extraction system design provided by the owner to the final design stage to enable full-scale construction. Usually, this entails going from the 30% design level to 100% (Middleton 1995). While the hand-off of the project to the turnkey team at the 30% design level is typical, it is not uncommon for the hand-off to occur with a preliminary design package significantly less complete, for example, the owner may supply only site assessment data, vapor extraction pilot study data, and basic remedial objectives.

The preliminary design provided to the turnkey engineer usually includes information on the number, location, and construction specifications of extraction wells/trenches. It also includes data on vapor extraction rates and applied vacuums designed for each well. Estimates of expected VOC concentrations in extracted soil gas and data on vapor treatment efficiency requirements are provided. A preliminary piping and instrumentation diagram is usually provided to schematically illustrate the process flow and basic control logic. Finally, a site layout showing the proposed location of the vapor extraction system equipment relative to boundaries, buildings, and other key features will normally be included.

One of the foremost design tasks of the turnkey engineer is to work with vendors and suppliers to translate the performance specifications provided into specific equipment requirements. This work element encompasses the full range of equipment requirements for the system from identifying the make, materials, electrical rating, and model number of the vapor extraction blower(s) to determining the actual flow sensors and associated soil gas sampling ports of the equipment to be ordered. On-site availability of electrical service and other utility availability (e.g., natural gas for thermal oxidation), as well as material compatibility analysis, electrical classification, equipment lead-time estimates, value engineering, and other factors all play an important part in the final selection of performance-based equipment. Once the electrical system components are identified, the engineer typically develops the electrical schematics that illustrate the system power requirements and control system enabling the system to be safely operated and maintained.

The design engineer is also tasked with translating the performance-based specifications into site-specific construction plans and specifications. These details are developed by the engineer with the active involvement of construction personnel or contractor members of the turnkey team and through owner and tenant interviews, utility mark-outs, reviews of facility layout and grade, identification of health and safety issues, and constructability analysis.

Plans and specifications developed by the design engineer for a typical system include the optimum routing of piping from:

- each of the extraction wellheads to the building or structure where the major equipment components will be housed; and
- the equipment building to the nearest electrical power source and other necessary utilities (e.g., telephone, natural gas, storm/sanitary sewer, etc.).

Wellhead and trenching completion details are also typically developed by the design engineer with feedback from the construction manager to ensure access to the wells while protecting the piping from surface loads (i.e., vehicle traffic). Finally, the design engineer typically provides plans for any equipment buildings and foundations. The design and specification package is subsequently employed by the engineer to competitively procure the services of the constructor(s).

Once the extraction system design has been peer reviewed, reaches the 100% level, and has been successfully employed to develop construction specifications to contract the constructor(s), the design engineer's role changes from engineer to construction manager. The responsibilities of the design engineer in this capacity are similar, if not identical, to those described below for the engineer hired for the specific task of construction management under the design-bid-construct-operate approach.

4.1.3.2 Construction Manager

Construction management is an essential task in most construction projects. While this work element may be one of many that the turnkey engineer is tasked to perform, an engineer may specifically be contracted to perform construction management services under the design-bid-construct-operate approach. However, regardless of whether construction management is included in a larger scope of work (turnkey) or whether construction management is the engineer's only assignment, responsibilities of the engineer as a construction manager are essentially the same.

General activities associated with the installation of a vapor extraction system for which the construction manager may be responsible include:

- project management;
- health and safety;

- partitioning of work into subcontract specialties;
- permit acquisition;
- subcontractor procurement/management;
- equipment procurement;
- construction quality assurance;
- as-built documentation;
- field design change authorization;
- field testing (slump, compaction, hydraulic/pneumatic, equipment assembly, start-up diagnostics, etc.);
- documentation (manpower, materials, etc.);
- regulator, client, and tenant liaison; and
- communication with the owner.

Under the design-bid-operate-build approach, the engineer ordinarily assists the owner in bidding and selection of the constructor(s) in addition to developing the specifications. With this approach, the construction manager may or may not be picked by the owner prior to selection of construction firms. The procurement of the construction manager following contracting the constructors can result in a loss of continuity and efficiency, as the construction manager delays commencement of construction to study and digest the design and specifications.

In the turnkey approach, the construction manager, rather than the engineer, may partition the construction work into the specialty trades. Once partitioned, the construction manager identifies and isolates design elements and specifications that pertain to the particular construction or equipment specialty and distributes these specific portions of the design and specifications to qualified specialty contractors or vendors for bids. The construction manager subsequently selects the best specialty contractors or vendors on the basis of cost, experience, and other factors critical to the particular installation work. Subcontract agreements in the turnkey approach are subsequently signed between the construction manager and the specialty trade firms to perform the specified work. Finally, the construction manager oversees the performance of the subcontractors to ensure that the specifications are met.

Where the construction management firm has some capacity to perform construction work, a fewer number of subcontracts may be required. On the other hand, an engineering consulting firm with few, if any, in-house construction capabilities, may require subcontracting of all construction work elements. Listed below are some of the more common specialty service areas associated with the installation of vapor extraction systems:

- drilling/well installation;
- waste management, characterization, and hauling;
- laboratory services;
- utility locators;
- surveyors;
- permitting services;
- excavation/trenching/grading/restoration;
- mechanical/plumbing;
- electrical;
- building construction;
- foundation construction;
- saw cutting;
- concrete/asphalt paving;
- equipment and controls (including package vapor extraction systems);
- specialty fabrication;
- security; and
- dewatering/water management/storage.

In addition to the verification of subcontractor conformance to construction specifications, the construction manager is responsible for ensuring that the construction work force complies with the facility's specific health and safety requirements as well as any local, state, and federal requirements. For example, the construction manager must ensure that construction workers who are likely to come into contact with hazardous constituents have the necessary training and be involved with a medical surveillance program consistent with the federal regulations (e.g., OSHA 1910.120). Electrical installation/troubleshooting work should be monitored by the construction manager to ensure that proper lock-out tag-out procedures are used. Where the potential exists for accumulation of explosive vapors in a work area (e.g., NEMA 7-rated areas including wellheads and piping trenches), the construction manager should enforce continuous vapor monitoring, especially when sparking or abrasion tools are being used in the area. Another health and safety consideration for which the construction manager is responsible involves ensuring that confined space work is completed by trained personnel in accordance with appropriate methods.

Under the design-bid-construct-operate approach, the project schedule is often developed by the constructor. In contrast, under the turnkey approach, the engineer or the construction manager may develop the construction schedule. In either case, schedule maintenance is an additional important responsibility of the construction manager. The efficiency and overall cost of vapor extraction implementation projects is often determined by the successful sequencing of individual construction components around site- and project-specific constraints. The duration of each work step in the critical path of the project must be accurately forecasted to avoid costly standby time and scheduling conflicts with the subcontractors. Where the project schedule has not appropriately forecasted the duration of a construction event, the construction manager must evaluate the impact of the change on the overall project schedule and identify cost-effective means of getting the project back on schedule. There are two basic methods that the construction manager can employ for schedule development and maintenance: (1) critical path method (CPM) and (2) program evaluation and review technique (PERT). However, CPM is the most widely used and preferred scheduling method as the size and complexity of vapor extraction implementation projects do not generally warrant the use of probabilistic models.

In the construction management role, the engineer is also responsible for verifying and documenting that the installation is consistent with the design specifications. Consequently, the engineer is responsible for conducting or overseeing and documenting the independent verification tests. For example, the vapor extraction system specifications may call for a minimum degree of piping slope from the equipment building to the extraction wells. To ensure that this specification is met, the construction manager may survey a number of the piping legs before the subcontractor is authorized to backfill the trenches. Other examples of the many tests or observations that can be performed by the engineer to verify conformance to the design and specifications include:

- concrete slump test;
- concrete compression test;
- soil compaction tests;
- trenching backfill sieve analysis; and
- pneumatic/hydraulic piping leak detection.

Typically, the construction manager does not have the authority to alter the design of the vapor extraction system due to unforeseen field conditions or construction circumstances (unless the construction management is being performed under a turnkey contract). The engineer is typically made available by the owner to provide input on design changes based upon the input from the construction company and the construction manager. However, if construction management is awarded to the owner's consulting engineer, the owner may defer field design changes to the engineer. It is the responsibility of the construction manager to document field design changes regardless of their origin.

An important element of the engineer's role in construction management is construction monitoring. Diligent construction monitoring and documentation is key to a project's success as this activity provides the first link in the communication chain that allows for informed decisions. A separate discussion of construction monitoring/oversight responsibilities of the construction manager is provided below to emphasize the importance of this engineering role.

4.1.3.3 Construction Overseer

A primary role of the engineer responsible for construction monitoring is to oversee the construction activities and to report progress and problems to the construction manager, the owner, or both. If the overseer finds that work is being performed outside of the specifications, the deficiencies are documented, and the contractor is notified of the findings by the engineer if the work is being completed under the design-bid-construct-operate approach, the problems are promptly shared with the owner. Contractors that do not take corrective action on their own will normally be directed to do so by the construction manager, owner, or both. If the constructor(s) are directly contracted by the owner, the overseer is typically not in a contractual position to directly instruct the contractors.

The overseer is also responsible for maintaining documentation and reporting field observations. These observations may include a daily record of:

- construction firms present;
- manpower by firm;
- machinery by firm;
- materials/quantity imported/exported by firm;
- work completed;
- problems encountered;
- solutions implemented;
- out-of-scope work;
- compliance with health and safety requirements; and
- quality assurance testing (i.e., pipe integrity, concrete specification, and equipment operation, etc.).

The recording of these and other site observations is a primary function of the overseer, and the value of such information should not be underestimated. This information may be employed by the construction manager and/or owner to validate:

- contractor invoices;
- change order requests;
- standby time cost repercussions;
- uncontrollable costs associated with a *force majeure*;
- contractor safety procedures; and
- conformance to installation design specifications.

The field observation documentation can also be a valuable tool during the system startup/troubleshooting and operation phases of the project. This is particularly the case where field design changes were made that unintentionally affect system performance.

4.1.3.4 Operator

As the operator of the remediation system, the engineer has several key responsibilities. First, the engineer must ensure that the system is operating safely at all times. The engineer must also ensure that the system continuously meets its permit requirements and, where necessary, take proactive steps to avoid any potential permit excursions. System data need to be reviewed and evaluated by the engineer to ensure that the equipment is operating within design limits and that the system is operating as efficiently as possible.

4.1.4 Construction Activities

4.1.4.1 Drilling/Well Installation

Vapor extraction system wells are often installed by drilling into the soils to a predetermined depth and then installing a well that is screened over a particular interval. Particular care must be taken during the installation to ensure that the well screen is placed at the appropriate depth, that a clean, granular sand pack is placed in the annular space between the well screen and the boring wall, and that an adequate bentonite seal is placed in the boring above the well screen to prevent the short circuiting of air flow during system operation. It is imperative that the well construction details developed during the design are implemented as intended.

4.1.4.2 Earthwork

Earthwork for vapor extraction system installations typically involves excavation and relocation of pavement and/or soil. These activities often begin following the installation of the remediation system wells. Initially, pavement is cut along the planned piping runs, and pavement and soils are excavated to form the piping trenches. The base of the trench is normally excavated to provide a uniform slope toward the vapor extraction wells from the equipment compound. Typically, piping placed within the trenches is bedded in an imported self-compacting granular material (e.g., pea gravel or washed crushed stone) prior to backfilling and trench completion with additional imported material or compacted native soil. Excavation of the equipment building foundation footings and any associated grading often occurs concurrently with the excavation of the piping trenches. The trenches are paved once the backfill compaction has been verified and the appropriate specified standards have been met.

4.1.4.3 Mechanical

The primary mechanical tasks required for an installation consists of the construction of the vapor extraction piping network. One of the first mechanical activities is constructing piping from the vapor extraction system wellheads to the equipment compound. This activity may involve the plumbing of individual piping spans from the equipment compound to the vapor extraction wells, manifolded piping, or some combination of the two. Mechanical work also typically includes the manifolding of vapor extraction piping entering the equipment building, which allows for adjustment of the vapor extraction system operation from the equipment building. The manifold installation completed by the mechanical contractor typically includes instrumentation (e.g., vacuum gauges, switches, transmitters, etc.), control valving (e.g., isolation, balancing, etc.), and sample ports. Manifold piping is connected directly to the vapor extraction blower system.

The basic mechanical components of the vapor extraction blower system can consist of interconnected piping, valving and instrumentation associated with a moisture separator, particulate filter, blower silencer(s), blow-back loop, and discharge stack. Aqueous process piping that may be included in a vapor extraction blower system includes that interconnecting the moisture separator to the condensate holding tank, a transfer pump, and the discharge outfall. Should emission control equipment be required, relatively minor additional piping (as required for granular activated carbon adsorbers) to significant supplementary mechanical work (as required for a gas-fired thermal oxidizer with wet scrubber) may be necessary.

Prior to backfilling the piping trenches, the mechanical contractor typically must demonstrate proper workmanship by leak testing the piping. Such testing is evaluated for several reasons. First, leaks in piping can lead to reduced system performance and effectiveness (e.g., where blower flow capacity is partially absorbed by ambient air entering through vacuum piping leaks). Second, leaks found during installation or start-up activities can identify areas where a greater potential for future integrity problems may exist (e.g., a PVC slip coupling where a contractor has failed to use glue) that could result in future catastrophic piping failure. Third, leaks may result in hazardous vapors entering unexpected areas. Lastly, the leaks may result in fugitive emissions and/or surface water discharges that are not permitted.

Pipe testing associated with vapor extraction system installation is generally completed in at least two phases. The first phase often occurs during trenching and prior to pipe burial. Once the remediation equipment has been secured inside the equipment building and mechanically and electrically interconnected, the abovegrade piping is tested.

The most common method of piping leak detection is the hydrostatic test (Nayyar 1992). In this method, a segment of piping is filled with water at ambient temperatures and pressurized to between 1.25 and 1.5 times the design operating pressure of the piping before being isolated from the pressurization pump. The pressure in the piping is subsequently monitored using pressure gauges located at both ends of the piping segment over a specified period of time. Often, the required period of time for monitoring the pressure condition in the pipe is specified to be a minimum of one hour. The piping segment passes the tightness test if the pressure in the pipe does not increase or decrease above or below a tolerance interval during the specified period. A commonly used tolerance interval is 2% of the applied pressure.

Piping systems may also be tested pneumatically. For this method, piping is typically pressurized using clean, oil-free air or nitrogen gas to a pressure equal to 110% of the design operating pressure. Similarly, a vacuum 10% greater than the design vacuum can also be used. Similar to hydrostatic testing methods, the piping segment is isolated once pressurized and the pressure is monitored at both ends of the segment over a period of time. Typically, the pressure within the piping must remain within 2% of the applied pressure over a minimum of one hour for the segment to pass the integrity test. During pneumatic pressure testing, soapy water is applied to the outside of the piping to locate small piping or fitting leaks so that they may be quickly repaired.

These descriptions of hydrostatic and pneumatic pipe testing procedures explain the typical methods used during vapor extraction system installations. However, specific testing requirements and criteria for passing an integrity test vary based on the construction standards specified by the engineer.

Regardless of test method (hydrostatic or pneumatic) and specifications, the contractor should know the pressure rating of each piping segment being tested. In addition, on each of the piping systems being tested, the contractor should place a relief valve that is set to release the pressure if (1) the pressure exceeds the test pressure by a predesignated percentage or (2) the pressure approaches the piping pressure rating. Typically, the pressure relief valve is set to open if the pressure in the pipe exceeds the test pressure by 10% while remaining at least 10% below the pressure rating of the pipe.

4.1.4.4 Electrical

A separate electrical service from the utility may be brought to the remediation site or electrical power may be tied into the existing power grid at the facility. In either case, the power is typically brought to a pole adjacent to the equipment compound where a disconnect switch and service meter may be installed. A circuit-breaker panel is fed by the service to control the distribution of power to the individual electrical components of the system (e.g., motors, lighting, heating, ventilation, receptacles, instrumentation, telemetry, etc.). For relatively simple systems (i.e., minimal controls and automation), the power distribution panel may feed electrical power directly to the vapor extraction system blower(s) and pump(s). However, for more complex systems where a greater number of controls govern operation, the power distribution system may feed directly into a PLC that distributes the power to the pumps and blowers when the instruments indicate that the appropriate motor should be energized.

Conditions that can be monitored to control vapor extraction system operation and that require installation of electrical wiring to the sensor/transmitter include gas composition, explosive vapor concentration, vacuum, pressure, temperature, air flow, and water level.

4.1.4.5 Concrete

The concrete work required for the installation of vapor extraction systems is typically minimal. It has two primary uses: (1) repaving areas that were excavated to install the piping grid, and (2) construction of the equipment building foundation. Concrete is often employed to cap piping trenches where the trenches cross driveways and other vehicle traffic areas. In such cases, concrete provides a monolithic bridge across the piping trench to evenly distribute traffic loads and to compensate for areas where the backfill in the piping trenches has settled. It has advantages over an asphalt cap because the asphalt surface is much less rigid and is prone to sagging. If an equipment building is to be constructed to house the vapor extraction equipment, a foundation is excavated and forms are constructed in preparation for pouring of the concrete footings and pad. Concrete pad construction ranges in complexity from a simple slab-on-grade to a heavily reinforced structure, depending on the system needs and local building codes. The concrete specifications and testing requirements (e.g., slump, compression strength, etc.) are normally developed with the design, and the installation is completed in conformance with the developed requirements.

4.1.4.6 Building

Depending on the design specifications and local building code requirements, buildings constructed to house vapor extraction equipment may be preconstructed, prefabricated, preengineered, and/or constructed on-site. Building materials can include wood, concrete blocks, or sheet metal. For smaller systems, it is common to have the vapor extraction equipment preassembled and shipped within an equipment enclosure. Larger systems that require more interior space often require the on-site erection of preengineered sheet metal buildings. Regardless of the specific type of building constructed, it should be adequately anchored to its foundation and connected to the electrical grounding system. Specifications for building construction are typically included with the system design.

4.1.4.7 Equipment Assembly

During the 1980s when the first vapor extraction systems were first installed, it was common for the system components to be assembled at the installation site. Blowers were secured to the equipment pad and mechanically and electrically interconnected with moisture separators, holding tanks, vapor treatment equipment, and instrumentation and controls. Since the 1980s, with recognized need to increase construction efficiencies and lower installation costs, the practice of assembling system components on-site has fallen from favor. Now, equipment manufacturers are often tasked with preassembly of equipment onto skids and pretesting the equipment assemblies at the factory prior to shipment to the site. Once the equipment arrives on-site, it is typically ready for operation after a few relatively minor mechanical and electrical connections are made. Since the prefabrication of the equipment in such cases involves both mechanical and electrical work, the design construction specifications developed in these areas apply equally to the off-site work as well as the on-site construction activities. Care must be taken to inspect the prefabrication work to verify conformance with specifications prior to shipment to the site.

4.1.4.8 Site Restoration

Following construction, a short period is typically allotted for returning the work area to as close to its preconstruction condition as possible. During this period, property damaged or destroyed by the contractor during system installation is fixed or replaced by the responsible contractor. Reparations often include replacement of paving that was damaged by the contractor's heavy equipment. Additionally, where use of heavy equipment on unpaved surfaces during earth moving activities has resulted in the formation of ruts, the restoration work includes grading and revegetating these areas. The contractor is typically required to replace all landscaped vegetation that was destroyed during construction with equivalent varieties and sizes. Finally, all contractor equipment, materials, and construction debris are removed from the site during this phase.

4.1.5 Construction Precommissioning Checklist

The following construction precommissioning checklist is adapted in large part from the US ACE (1995).

Subsurface

- Wells/trenches installed to specifications
- Wells purged/cleaned
- As-built elevations of well screens field-checked
- Monitoring points installed
- Instrumentation installed on wellheads
- Underground piping to wells installed/tested
- Piping flushed/cleaned
- Strainers/filters installed/cleaned
- Valves installed and operation verified
- Pressure test complete

Housing, Blowers, and Pumps

- Foundations complete
- Blowers, pumps, and motors bolted in place
- Vibration dampers installed
- Coupling alignment/level to specifications
- Pipe connections installed/tested
- Seals intact (no leaks)

Electrical

- Grounding installed/checked
- Lighting/HVAC functional
- Lockouts/covers/panels in place
- Blower rotation verified
- Disconnects in sight of unit being controlled
- Controls/alarms and interlocks functional
- Power connected to monitoring instruments

Mechanical Units

- Instruments calibrated
- Air treatment system installed/functional
- Auxiliary fuel (if needed) operational
- Aftercooler system functional (if needed)

4.2 Start-up Procedures

Once a vapor extraction system has been installed, it is prudent to follow a carefully planned and orchestrated start-up procedure. Following a developed start-up protocol will not only minimize the potential health and safety hazards that exist with initial operation of such equipment, but also reduce the potential of incurring additional costs and extending the implementation schedule by operating equipment outside of manufacturer specifications.

While the variability in site settings, contamination, system designs, and equipment specifications suggest that a customized start-up plan be developed for a particular installation, many of the start-up procedures are common to all installations. The focus of this section is on procedures that are likely to be common to a wide variety of vapor extraction systems. First, a discussion is provided on methods to test individual components of a system. This is followed by testing procedures for the system as a whole, and a general start-up checklist.

4.2.1 Component Testing

One of the most important start-up tasks is component testing. Completion of this testing ensures that the system components are being operated in accordance with manufacturer recommendations, the system will operate safely, and the control logic programmed into the system is consistent with the design. Minimizing the importance of component testing during the start-up phase can lead to several undesirable consequences including premature equipment failure, voided warrantees, contractor stand-by time, costly system troubleshooting, delayed system startup, misdiagnosis of performance variances, permit violations, and personnel injury. A discussion of prudent system diagnostic testing is provided in the following sections.

4.2.1.1 Power Supply

A number of precautions need to be taken early in the startup in connection with the power supply to individual system components. These precautions need to be taken to protect operators of the system as well as to ensure that the equipment is adequately protected. The precautions include:

- verifying the proper grounding of equipment;
- cross-checking the supply voltage with motor name-plate voltage;
- confirming sizing of thermal magnetic circuit breaker ratings for each motor; and
- testing ground-fault circuits.

In addition, it is essential that three-phase motors be checked for proper rotation prior to operating the motors for any extended period of time. Motors generally operate more efficiently from three-phase power sources than a single-phase supply. For this reason, design specifications for the blowers, pumps, and fans of vapor extraction systems typically call for motors that can accommodate three-phase power if it is available. While the three-phase motors provide increased efficiency, they can be inappropriately wired because two of the wiring legs can be connected interchangeably, resulting in an opposite rotational direction from that intended.

Improper rotation of an impeller will, at a minimum, result in poor blower, fan, or pump performance. Specifically, the improperly rotating equipment will be unable to achieve the design pressure and flow conditions. In the worst case, the impeller may be designed to rotate in only one direction, and prolonged rotation in the opposite direction could cause serious damage to the equipment.

Testing for rotation during startup consists of "bumping" or energizing the motor for a fraction of a second while monitoring the equipment impeller. The perceived direction of rotation of the impeller is compared to the rotation specified by the manufacturer. Typically, the design rotation of the impeller is imprinted on, or cast into, the housing of the equipment. If rewiring is necessary, the procedure is repeated to verify that the appropriate action was taken.

4.2.1.2 Performance

Once the basic electrical testing has been completed, the performance of individual system components should be checked against manufacturers' specifications. For vapor extraction blowers, performance testing includes measurement of the initial running amperage and comparison of the measured value to the manufacturer's tolerances. The initial running amperage of the vapor extraction blower and other motors should be recorded as baseline conditions from which future operating conditions can be compared. The vapor extraction blower performance testing should also include measurement of air flow rates under various simulated vacuum/pressure conditions to establish the field blower performance curve. This curve should closely resemble the manufacturer's performance curve for the blower. Significant deviations between the field blower curve and the manufacturer's curve warrant further investigation prior to placing the system in operation.

4.2.2 System Testing

Following the successful testing of individual components, the vapor extraction system is tested as a unit. Such testing entails verification that the multiple components of the system will operate simultaneously, that communication between instruments and the controller is accurate and functional, and that the control logic conforms to the design. The following discussion covers instrument calibration and diagnostic testing.

4.2.2.1 Instrument Calibration

For economic reasons, vapor extraction systems are typically designed to operate unattended over extended periods. The automated operation of vapor extraction systems is facilitated by use of electronics to monitor critical system conditions and to control the operation of system components. Successful use of electronics in a design yields a system that operates safely yet does not strain the system, causing frequent automated system shutdowns. Reliable automated operation also requires that electronics be thoroughly calibrated and tested during system startup and at regular intervals during operation.

Calibration of the in-line mechanical and electrical monitoring and control instruments during the start-up period is critical to successful operation. Mechanical gauges (e.g., vacuum/pressure) are zeroed while the system is at idle and cross-checked with an independent gauge once the system has been activated. The linear voltage/current output of system transmitters (e.g., flow, pressure, level) is calibrated to expected ranges of conditions using independently-calibrated field instruments. Finally, the set-points on instrumentation switches are checked to verify that the switches activate at the design low and/or high parameter condition(s).

4.2.2.2 Diagnostic Testing

After initial calibration of instruments, the control logic programmed into the system can be checked to verify the shutdown protocols of the design. This check is generally performed during the start-up activities by simulating an operating condition that is critical to a control sensor and observing the subsequent automated response. For example, an in-line LEL meter is to terminate operation of the vapor extraction blower(s) but allow continued operation of a ventilation blower if vapor concentrations of 10% LEL are detected. A local alarm is to be displayed while a remote operator is to be notified via telephone of the alarm condition. To test the control logic, the LEL sensor is exposed to a 10% LEL calibration gas while the system is fully operating and the sequence of programmed responses is confirmed.

During the start-up phase, the alarm conditions associated with each switch and transmitter in the control loop are simulated, and the system's automated response is monitored and compared to design protocols. The system should be started and stopped over a dozen times to ensure that the system shutdown protocols have been thoroughly checked. After these simulations of alarm conditions have been performed and the system responses found to be as designed, the vapor extraction system is ready for operation.

4.2.3 Checklist for Startup

The following checklist is typical for startup of a vapor extraction system.

- Remove debris from piping interior (PVC shavings, soil, etc.)
- Complete pipe integrity testing
- Eliminate piping blockages
- Appropriately position all system valves
- Orient valving on blower piping in start-up configuration for least flow resistance
- Cross check motor supply voltages with motor plate voltages
- Cross check thermal magnetic circuit breaker ratings with motor amperage specifications
- Verify that motors and hand switches are properly grounded
- Collect background data (e.g., static soil pressure, VOC concentrations, depth to water, etc.)
- Secure and post requisite discharge permits
- Check equipment lubricating fluid levels
- Verify proper rotation of motors
- Record initial running amperage of motors
- Recalibrate all in-line instruments

- Check switch set-points
- Compare and adjust sensor transmitter spans relative to actual conditions
- Simulate alarm conditions; verify automated operations
- Confirm remote access to telemetric data
- Reconfigure valving to achieve design vacuum/flow
- Compare blower/pump performance to manufacturer's performance curves
- Check vacuum at wellheads to confirm minimal piping headloss
- Record influence vacuums at influence monitoring wells
- Collect influent and effluent vapor samples for baseline field and laboratory analysis

4.3 Maintenance

A successful vapor extraction system design and installation does not directly translate into a successful remediation. Without the development and full implementation of an appropriate operations and maintenance (O&M) plan, even the best system design could result in a faculty remediation program. An O&M plan is typically developed following the system design.

O&M plans vary in content and complexity depending on the specifics of a particular installation. Factors that contribute to the customization of O&M plans include a variety of site conditions (setting, contaminants, site use, geology, hydrogeology, etc.), scale of the remediation system, and type of remediation equipment employed.

A generic table of contents for an O&M manual is presented below to help in identifying the main issues. The items listed are by no means exhaustive for any particular system, the table is simply provided as an aid in developing an O&M manual that provides the information required by a qualified operator to operate a system and meet the overall remedial objectives for a site.

O&M Manual Sample Table of Contents

- 1.0 Introduction
  - 1.1 Purpose of the O&M Manual
  - 1.2 O&M Manual User's Guide
  - 1.3 Remedial System Overview
- 2.0 Remedial Objectives
  - 2.1 Short Term
    - 2.1.1 Operate Using Design Parameter Values
    - 2.1.2 Modify Operational Parameters to Maximize Mass Removal
    - 2.1.3 Maximize Cost-Effectiveness of Operation
  - 2.2 Long Term
    - 2.2.1 Attain Clean-up Goals
    - 2.2.2 Minimize Time of Remediation
- 3.0 Remedial System Description
  - 3.1 Facility Layout
  - 3.2 Remedial System Instrumentation
  - 3.3 System Component Descriptions
- 4.0 System Operations
  - 4.1 Operator Duties
    - 4.1.1 Daily Responsibilities
    - 4.1.2 Periodic Maintenance
    - 4.1.3 Certification
  - 4.2 Start-up/Shutdown Procedures
  - 4.3 Routine Operation and Operational Control
  - 4.4 Troubleshooting
- 5.0 Sampling and Monitoring
  - 5.1 Types of Samples

- 5.2 Sampling Locations
- 5.3 Sampling Frequency
- 5.4 Sample Tracking and Handling
- 5.5 Monitoring Procedures
  - 5.5.1 Overview of Standard Operating Procedures

6.0 Record Keeping and Reporting

- 6.1 Operation Forms
- 6.2 Monitoring Forms
- 6.3 Quality Assurance/Quality Control Procedures

7.0 Alarm Response Procedures

8.0 Safety

- 8.1 Contents of Health and Safety Plan
- 8.2 Injury Response

Possible Appendices

- List of Manufacturers' Literature
- Health and Safety Plan
- Spill Prevention, Control, and Countermeasure (SPCC) Plan
- Operation Logs and Inspection Forms
- Standard Operating Procedures
- As-Built Drawings

Although an O&M plan is typically unique to the particular remediation system for which it is developed, there are fundamental operation, maintenance, and safety elements that are common to all forms of vapor extraction systems. These common elements are discussed in the following sections.

4.3.1 Extraction Systems

Although a vapor extraction system may be ideally designed, flawlessly installed, and have the best O&M plan, success of the remediation relies heavily on maintenance of the system. Typically, a relatively large capital investment is made for the design, purchase, and installation of remediation equipment. The return on this investment can be measured by the percentage of time that the system is operable and progress is made in remediating the site. Equipment that is frequently idle due to poor maintenance results in a low return on the investment and increased project costs.

Maintenance requirements for vapor extraction systems vary according to the specific design and equipment employed in the system. Many of the maintenance procedures that must be followed are those that are specifically required by the equipment manufacturer. However, maintenance requirements that are typical of these types of remediation systems include:

- cleaning/replacing particulate filters;
- cleaning/testing level switches;
- changing oil/cooling fluids;
- changing/tensioning belts;
- disposing of accumulated condensate;
- blowing back accumulated condensate in system piping to the wells;
- visually inspecting of equipment, valves, piping, etc. for leaks, cracks, and wear;
- testing pressure/vacuum switches;
- replacing spent granular activated carbon adsorbers;
- replacing poisoned/spent catalysts;
- cleaning heat exchanger cooling fins;
- measuring motor amperage draw;
- inspecting/testing of pressure/vacuum relief valves;
- calibrating instruments; and
- inspecting/testing alarms/controls.

Special maintenance procedures for select system components are discussed below.

4.3.2 Vapor Treatment Systems

Vapor treatment systems should be operated and maintained in strict adherence to manufacturer's recommendations. Generally, monitoring the efficiency of a vapor treatment system over time provides a good indication of the success of a maintenance program. A measured reduction in adsorption capacity in a granular activated carbon treatment system could signal that excessive moisture is being permitted to enter the carbon vessels to compete with the constituents of concern. Reduced treatment efficiencies in catalytic oxidation systems could signal the premature poisoning of a catalyst or simply that one or more of the catalyst beds requires regeneneration. The manufacturer of the treatment equipment should be contacted to see if additional maintenance activities are warranted if approved maintenance procedures do not provide the anticipated treatment efficiency results.

4.3.3 Wells, Trenches, and Well Points

Generally, the maintenance requirements associated with the wells, trenches, and well points of a vapor extraction system are minimal. However, inspection of these components should be completed on a regular basis, especially when they are located in roadways. Truck traffic, deicing chemicals, and snow removal equipment can damage surface expressions of each of these components. Specific maintenance tasks related to these components that should be completed on a routine basis include:

- extraction of accumulated water in wellhead vaults;
- removal of accumulated sediment in wellhead vaults;
- inspection/replacement of well seals/locks;
- inspection of wellheads for frost heave and grout integrity;
- inspection of pavement for loss of integrity — patch/seal where required; and
- inspection of pavement over trenches for settlement.

4.3.4 Piping

Above-grade piping should be regularly inspected for corrosion, heat damage, stress cracks, sunlight (UV radiation) damage, and leakage. Piping damaged during system operation should be replaced, and corrective measures should be taken to prevent repeated piping failures. Typical corrective measures include adding pipe bracing/support, installing piping insulation, changing piping material, and replacing "sticky" valves.

4.3.5 Equipment Enclosure

The equipment building should be regularly inspected for leaks and structural damage and repaired, as needed, to help ensure the continuous safe operation of the vapor extraction system equipment.

4.3.6 Safety Considerations

Operation of vapor extraction systems presents a number of health and safety hazards to the operator and the surrounding population. Procedures must be in place to address these potential hazards during system operation. The most basic health and safety consideration for the operator is that the system is likely processing hazardous chemicals, and therefore, the operator should complete training and participate in a medical monitoring program in accordance with OSHA 1910.120. Other operational hazards that need to be considered during system operation are discussed below.

4.3.6.1 Fire Safety

Fire safety is an important consideration during the operation of any remediation system and it is of particular importance when the installation is at an active facility where flammable and/or toxic chemicals are present. The moderate level of risk of fire presented by the electrical equipment associated with an enclosed vapor extraction system is significantly increased by the operation of the equipment and the processing of combustible VOCs. Equipment and piping must be carefully monitored and maintained to guard against the accumulation of hazardous, if not potentially explosive levels, of VOCs anywhere in the system or equipment building.

Prudent measures that should be followed during operation of a vapor extraction system include the following:

- placement of fire extinguishers both inside and outside the equipment building and routine inspection of the extinguishers;
- enforcement of a no-smoking policy in and around the equipment building; and

- implementation of a formal “hot-work” permitting program that requires that a permit be obtained prior to using any sparking or abrasive/friction-generating equipment or electrical hand tools. (The permit should require results of vapor monitoring prior to approval.)

4.3.6.2 Air Quality

The extraction of soil gas containing hazardous chemicals presents additional operational safety hazards. First, fugitive vapors from the extraction system have the potential to accumulate in the equipment area and could result in operator exposure to the toxic chemicals. Second, extracted vapors may become more concentrated than the system was designed to accommodate, resulting in excessive VOC emissions to the atmosphere.

Prudent measures that can be taken by the operator to reduce the risk of exposure to extracted VOCs include the following:

- monitor the concentrations of VOCs in the equipment building prior to entering and while inside;
- wear a protective respirator when sampling soil gas piping that is under pressure; and
- reduce soil gas extraction rates when concentrations of VOCs in the vapor stream approach the treatment limits and/or permitted levels and increase the effluent monitoring frequency until the concentrations plateau.

4.3.6.3 Physical Hazards

Equipment for vapor extraction systems can present many potential physical hazards to the operator of the system and to others. Potential hazards include those associated with tripping and falling, impacting, entrapment, entanglement, exposure to hot equipment, and excessive noise.

Blowers used in vapor extraction systems are often decoupled from their motors and belt-driven. Normally, a protective cage is provided with these systems to prevent entanglement during system operation. To ensure safe operation of this equipment, the operator should routinely inspect the protective cage to verify that it is secure. Following belt tensioning or any other maintenance task that requires removal of the cage, the operator should require that the cage be resecured before the system is restarted.

Piping exiting blower systems can hot enough to burn skin. Where the operator observes such a condition and where there is a reasonable potential that maintenance or monitoring personnel could contact the piping, the operator should insulate the piping and periodically inspect and maintain the insulation for the duration of the project.

Extraction wellheads also require periodic inspection and maintenance. For wellheads that are flush with the ground surface, inspection and maintenance can typically be performed only following removal of vault lids. Left unattended for any period of time, these open wellhead vaults present a serious trip hazard to anyone with access to the area. At a minimum, the operator should employ traffic cones or barricades around any open wellhead.

Equipment used in a vapor extraction system is generally secured to the floor or building walls during installation. However, the operator should regularly inspect the bracing of such equipment to verify that vibrations have not jarred the equipment loose, creating a potential fall/impact/entrapment hazard.

Blower systems that are frequently employed in vapor extraction systems generate a significant level of noise. Even when equipped with silencing equipment, these blower systems can generate enough noise to be damaging to human ears in a relatively short period. In such instances, the operator should require that all entrants to the equipment building wear hearing protection.

4.4 Performance Monitoring

Design of vapor extraction systems is, for all practical purposes, a continuous process that begins with the initial conceptual design and continues after the system is installed and operating. Monitoring data are a key basis for assessing system performance, calibrating models, and making necessary operational changes and equipment modifications. This section discusses data presentation options for full-scale continuously operating systems. There are a wide range of monitoring options and it is up to the practitioner to select monitoring requirements based on the particular need for information. For example, there are typically three types of system monitoring that are performed for vapor extraction systems: (1) *process monitoring,* in which data are collected to evaluate whether the vapor extraction equipment continues to operate within manufacturers' recommended tolerances; (2) *compliance monitoring,* in which data are obtained to document compliance with air and water discharge permit conditions; and (3) *performance monitoring,* in which data are collected to evaluate the effectiveness of the system in remediating the site. Depending on the level of complexity of a system, the practitioner may elect to emphasize one form of monitoring over another in order to best meet the intended objective. This chapter focuses on performance monitoring.

The following requirements are presented in relative order of importance in assessing system performance. While there is flexibility in choosing monitoring strategies, there is a minimum level of information that must be gathered in order to make basic performance evaluation decisions.

4.4.1 Extracted Vapor Flow Measurement

The most straightforward means of assessing vapor extraction process performance is to monitor the flow and composition of the extracted gases. This is the minimum monitoring required and is conducted to track mass removal rates, compositional changes, and mass and vapor flow rates. Soil gas extraction rate measurements and soil gas analyses need to be completed for each of the extraction wells to assess the effectiveness of each and make adjustments accordingly. Interpretation of the data can lead to identification of permeability changes and mass-transfer limitations.

The actual flow rate (Q) may be measured by a number of means. It should be corrected to some standard volume per unit of time; i.e., (Q^*) at a standard pressure and temperature:

$$Q^* = Q(P / 1\ \text{atm})(293^\circ\text{K} / T) \tag{4.1}$$

where: P (atm) = absolute pressure measured at the flow rate measuring device

T (°K) = absolute temperature measured at the flow rate measuring device.

Examples of the most widely used expressions of flow rate units are scfm (this implies flow rates corrected to 1 atmosphere and 20°C). 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. To be able to express the measured flow rate on a standard basis (1 atm, 20°C), the pressure and temperature at the point of flow measurement must be known. Mass flow meters automatically correct for changes in temperature and pressure and typically are coupled with a flow totalizer, which provides valuable data for performing mass removal calculations. All extraction 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 of at least 10 pipe diameters away from constrictions); manufacturer guidelines should be followed closely.

4.4.2 Wellhead Pressure

Vacuum should be monitored at the extraction wellhead, typically with 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 at the wellhead 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 3.6a presents pressure and flow rate data for a vapor extraction system. The figure indicates that a permeability reduction occurred with time, as the flow rate decreased with time and the applied vacuum remained constant. In this case, the reduction was attributed to groundwater elevation changes (Johnson et al. 1991). Similar injection pressure versus flow rate plots should be made for bioventing systems that use air injection wells.

4.4.3 Extracted Vapor Quality

Extracted vapor quality is monitored to determine contaminant removal rates and assess mass-transfer limitations. At a minimum, composition measurements should include some measure of the target contaminant concentration. Respiratory gas measurements (oxygen and carbon dioxide) can provide an indicator of biological degradation activity when the contaminants are aerobically biodegradable. As discussed in Section 3.2.2.1, a variety of techniques are available for measuring contaminant concentration in the extracted vapors; the choice in a given situation may be dictated by regulations or permitting procedures.

For sites contaminated with mixtures of hydrocarbons such as fuels, time trends in boiling point distribution are valuable in monitoring the progress of a particular system. Near the end of remediation, it is expected that the majority of compounds in the C1-C8 range (the lightest, most volatile compounds) will be seen in limited concentrations in the extracted vapors, and the C8 -C12 compounds should dominate the boiling point distribution. Once the volatile and semivolatile compounds have been removed by vapor extraction, the remaining less volatile compounds (if they need to be removed) can be remediated by bioremediation. At that point in operation, depending on the cleanup levels for site soils, operation of the system may be switched to focus on bioventing (i.e., lower flow rates and/or pulsed operation).

4.4.4 Subsurface Vacuum Distribution

The vadose zone monitoring points should be periodically measured for soil pressure to ensure that the design zone of influence is maintained. As full-scale operation proceeds, soil permeability may be modified for the reasons discussed in Section 4.4.1. If "dead zones" (i.e., zones of soil that do not have significant air flow) develop, it is necessary to modify the vacuum applied to nearby wells to change the vapor flow pattern. The applied vacuum should be increased until pressure readings at the pressure monitoring points indicate that soil gas flow has been re-established.

4.4.5 Condensate Production Rate Monitoring

The air/water separator water level should periodically be monitored to determine the condensation production rate and how this rate changes under different environmental conditions. Condensation production will peak during cold weather as the moisture in the relatively warm soil gas condenses in manifolding. Correspondingly, drains in the manifolding should be checked more frequently during cold weather and after heavy precipitation events, as these are the periods when condensate is expected to accumulate in the largest volumes.

4.4.6 Mass Removal Rate Calculations

Concentrations of contaminants in vapor samples are most often reported by laboratories as parts per million by volume (ppm_v) (sometimes called µL/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 also be expressed as mass per unit volume of vapor, such as µg/m³ or mg/L. The basic relationship between partial pressure and mass per unit volume is:

$$C_{vapor}(\mu g / m^3) = C_{vapor}(ppm_v)\frac{10^{-6}MW}{RT} \qquad (4.2)$$

where: MW (µg/mole) = molecular weight of the contaminant *used to calibrate the detector* (may not be the actual contaminant being monitored)

R = gas constant (8.2° 10^{-5} m³-atm/mole-K), and

T = 293°K (20°C).

This equation is essentially the Ideal Gas Law where C_{vapor} (ppm_v) 10^{-6} represents the partial pressure of the gas being monitored. As previously mentioned, it is important to recognize that expression of gas concentrations in volume/volume units is meaningless unless the calibration compound is also specified. 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. For example, a gasoline vapor stream reported to have a total contaminant concentration of 100 ppm_v-methane (0.067 µg/m³) is not equivalent to a reported total concentration of 100 ppm_v-hexane (0.358 µg/m³).

For performance monitoring, vapor concentrations should be reported and recorded in mass/volume units, as this facilitates the calculation of removal rates (R_v, mass/time) and confusion is minimized. R_v is the product of the flow rate (volume/time) and vapor concentration (C_{vapor}, mass/volume):

$$R_v = Q^* C_{vapor} \qquad (4.3)$$

Here, the flow rate is expressed in standard units (Q^*) as most gas samples are analyzed from sample containers maintained at 1 atm pressure. To calculate contaminant removal rate over a given time interval, the concentration of target contaminant is assumed to be constant over that time interval. A cumulative contaminant mass recovered by volatilization (T_v, mass) can be computed by integrating the recovery curve over time:

$$T_v = \int_{t=0}^{t} R_v dt \tag{4.4}$$

4.4.7 Rebound Spike Concentration Monitoring

Several studies have indicated that when contaminant mass removal by vapor extraction becomes diffusion-limited, pulsed operation from individual wells is more efficient than continuous operation on a mass extracted per unit of energy expended basis (Hutzler, Murphy, and Gierke 1989; Crow et al. 1987). Pulsed operation of a vapor extraction well allows soil vapor to equilibrate with the surrounding soils via diffusion from solid phase to the soil pore space when extraction stops. When a vacuum is again applied to the well, the soil vapor extracted will contain higher concentrations of VOCs to the extent to which diffusion has occurred and has limited mass transfer during continuous operation.

To investigate the extent to which diffusion-limited transport is occurring at soils surrounding a particular well, a "rebound spike test" can be performed. In this test, the extracted vapor VOC concentration is first measured at the test extraction well during continuous operation. The vacuum at the test well is then shut off for a period of at least one week. The vacuum is then reapplied to the test well, and the VOC concentration in the vapors of the extraction well is immediately measured. The difference in vapor VOC concentrations during continuous operation and after restart is referred to as the *rebound spike*. The magnitude and duration of this spike can be used to determine the relative extent to which diffusion is limiting mass removal from soils within the zone of influence of the test well.

A series of rebound spike test results is often needed to provide evidence to support site closure. Favorable results will show a declining rebound spike (both in terms of extent and duration) in a series of rebound spike tests.

4.5 Operational Modifications

Modifications that can be made during the design stage to enhance the mass extraction rate are explained in Section 3.4. Once a vapor extraction or bioventing system is built, modifications may be made by adjusting the system operational controls in response to performance monitoring data.

Over time, the mass extraction rate from a well is expected to change in response to drying, wetting conditions (water table fluctuations), and removal of VOCs. Many practitioners refer to two distinct stages, the advection-controlled and the diffusion-controlled stages. The advection-controlled stage is indicated by sustained, high concentrations of VOCs in the extracted air from a vapor extraction well. In this case, the rate of volatilization of VOCs to the air stream in the subsurface is not limited. As the remediation progresses and the mass is removed, the rate of volatilization decreases, leaving diffusion as the primary controlling process. Under diffusion-controlled conditions, air flow may not be limiting the overall system mass removal rate at all locations at the site. When air flow is not limiting, alternate operational modes can be effective in maximizing mass extraction rates and reducing operational costs.

4.5.1 Balancing and Managing Air Flow

Control valves on the vapor extraction manifold can be adjusted while measuring the air flow from each well. During initial stages of a project, a balanced flow rate among all of the vapor extraction wells is typically desired. As the project progresses, wells yielding little or no VOCs can be turned off or flow rates can be minimized for diffusion-controlled wells and increased from extraction wells with the highest VOC concentrations (advection-controlled wells).

4.5.2 Targeting Residual Contaminants

Typically, a few vapor extraction wells in the most contaminated area will be the slowest to clean up. By adjusting the air flow and vacuum to concentrate on the remaining "hot spots," the cleanup process may be accelerated in these areas. Another approach is to use vapor extraction or monitoring wells near the residual mass to inject air while extracting vapor in say, one well, to create different air flow patterns in the subsurface. Installation of additional air infiltration wells in the residual mass may also increase mass removal. Finally, increasing the vacuum in a vapor extraction well may also be effective.

4.6 Quality Control

Prior to using analytical data for decision-making purposes, some data validation should be performed. In most cases, full validation in accordance with formal US EPA protocols is not required for site characterization or pilot test data. However, if comparisons to clean-up criteria are intended, full validation may be justified. At a minimum, data received from an analytical laboratory should be qualitatively assessed. A review of compounds detected in duplicates and blanks as well as the percentage of surrogate recoveries in matrix spike samples provides an indication of the quality of analytical data. The sampling and analysis plan must include appropriate quality control samples, such as duplicates, matrix spikes, and field and trip blanks at specified frequencies, usually as a percentage of the total number of samples collected.

The topics and issues that need to be addressed with regard to quality control during operation of a vapor extraction system are typically covered in the O&M manual.

5

DESIGN DEVELOPMENT FOR AIR SPARGING

5.1 Groundwater Remediation Goals

5.1.1 Selecting Design Objectives

As with vapor extraction/bioventing, engineers need to clearly delineate the design objectives for a sparging system. Identifying design objectives and constraints is the first step in the design process. The considerations include:

- *Primary Mass Removal Mechanisms* (volatilization or biodegradation). However, unlike vapor extraction systems, it is difficult to selectively increase either mechanism. Conditions favorable for volatilization of dissolved-phase contaminants out of groundwater are also favorable for partitioning of oxygen into groundwater. Still, a design objective may be to maintain aerobic conditions in the treatment zone.
- *Purpose of the Sparging System.* Some sparging systems are designed as dissolved-phase plume cutoff walls. These may consist of a line of sparging wells, a sparging trench, or a funnel-and-gate type array. Either way, they are intended to be a long-term containment approach to reduce dissolved-phase VOCs to some concentration before they reach a point of compliance. Other sparging systems are designed to address an entire dissolved-phase plume through a series of vertical or horizontal

sparging wells in close proximity. Treatment systems designed for cleanup have an operating life of months to a few years, but ultimately need to achieve some clean-up criteria for dissolved-phase contaminants throughout the treatment zone. Finally, a system may be designed to help address an LNAPL source zone. Such systems intensively aerate smear zone contaminants to attack the source of contamination. The success of such systems is evaluated by both dissolved-phase contaminants in the groundwater and residual soil concentrations in the smear zone and even in the vadose zone. Sparging systems are almost never employed to reduce mobile DNAPLs since there is little documentation to support such applications.

- *Type and Complexity of Operations.* The expected duration of treatment, size of the system, and identification of probable treatment operators may dictate the level of automation and sophistication required in the design and controls.

When implemented for groundwater treatment, sparging involves the volatilization of at least some of the dissolved-phase contaminants into the vadose zone. Many times, the aeration of the vadose zone that is associated with groundwater sparging can be an oxygen source for vadose zone contaminant biodegradation. This is especially important at most fuel release sites where vadose zone biodegradation is a major part of cleanups. Thus, the layout and operation of such sparging systems needs to satisfy the objectives of both groundwater and vadose zone aeration. In most cases, a vapor extraction system will need to be designed to capture volatilized contaminants. In other cases, engineers may rely on natural vadose zone biodegradation to treat the volatilized contaminants. Such an approach requires that the natural attenuation of the vapor-phase contaminants in the vadose zone be monitored. In addition, operation of the sparging system may be limited by the assimilative capacity of the vadose zone for the volatilized contaminants. In either case, the effect of sparging on the vadose zone and overall site closure issues must be considered.

Conceptual site models that show contaminant distribution, aeration from the sparging system, and effects of aeration on contaminant volatilization and biodegradation are key to final project success. Specific site features that may affect implementation, such as building constraints, changes in soil types, subsurface structures, and access constraints, also need to be shown on conceptual models. The conceptual model provides the means on which to base the more quantitative evaluation of sparging system flow rates, well sparging, and mass removal.

5.1.2 Establishing Groundwater Clean-up Goals

Traditionally, groundwater clean-up goals have been the maximum contaminant levels (MCLs) established under the Safe Drinking Water Act. For most common contaminants treated with sparging (BTEX and chlorinated solvents), the MCLs range from five to tens of parts per billion. Today, MCLs remain clean-up goals at many sites, particularly those with groundwater that may be used for human consumption. However, as discussed in Section 3.1.2, the risk-based corrective action model can also be applied to groundwater concentrations. Actual groundwater clean-up criteria vary widely depending on the end use of the site, the point of compliance, and the location of potential receptors. For example, the benzene MCL is 5 µg/L. An allowable concentration for benzene in groundwater at a nonresidential site may be tens of parts per billion. Allowable benzene concentrations in a groundwater discharge to surface water may be hundreds of parts per billion. Through the use of more sophisticated fate and transport models that account for biodegradation before the point of compliance, benzene clean-up criteria significantly higher than these values may be acceptable. As with soil concentrations, a comprehensive approach to establishing groundwater clean-up concentrations is beyond the scope of this monograph, but an adequate understanding of clean-up criteria is critical to the design of a sparging system. The following sources can be consulted for further guidance:

- *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites* by the ASTM (E-1739-95);
- *The Interim-Final Risk Assessment Guidance for Superfund* (Part A and Supplemental Guidances) US EPA, December 1989; and
- State-specific clean-up guidance.

Groundwater clean-up criteria need to be determined when design objectives are set. For many sites, groundwater clean-up levels may be technology-based instead of performance-based (i.e., clean-up criteria are set depending on what the system can achieve).

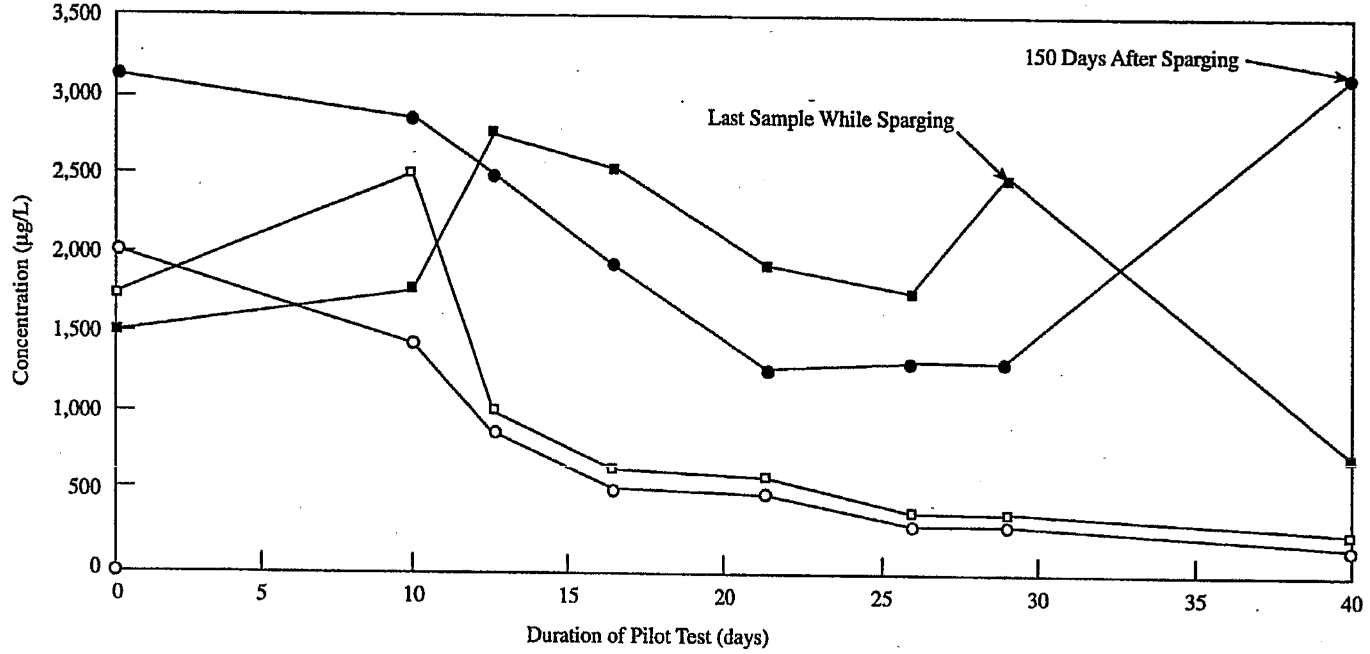
5.1.3 Measuring Groundwater Clean-up Criteria

Measuring changes in dissolved-phase groundwater concentrations with time and comparing these concentrations to clean-up criteria is a simpler task with groundwater sparging than assessing changes in soil concentrations during vapor extraction. In general, groundwater samples are collected from a series of monitoring wells and piezometers (small diameter well, e.g., 1 in.). For systems designed for long-term plume containment, groundwater monitoring wells downgradient from the sparging system and outside of the direct influence of the sparging system are used to monitor for compliance. Wells on either edge of the line of sparging wells should be monitored for plume displacement. Typically, monitoring wells screened over the entire impacted depth of the aquifer are typically used to assess groundwater quality.

For systems designed to address an entire plume or source area, groundwater monitoring is best conducted at vertically and horizontally discrete areas through the plume. There can be great variation in treatment effectiveness over relatively short horizontal and vertical distances. For example, Figure 5.1 shows the changes in four groundwater monitoring piezometers at various vertical and horizontal distances from a sparging well. All four piezometers were within 6 m (20 ft) of the sparging well, yet show different concentration fluctuations. Collection of such data indicates where the system is less effective and consequently where operational or design changes are required. Typically, a combination of monitoring wells around the sparging target zone and monitoring piezometers within the sparging zone is appropriate for system monitoring. At a minimum within the treatment zone, two separate monitoring piezometers, each with at least two vertically discrete sampling intervals, should be used to assess system performance. More monitoring peizometers may be required for larger sites. Using solely traditional monitoring wells does not provide adequate data to assess system performance.

When assessing cleanup, it is necessary to distinguish between dissolved-phase VOC concentrations that may be observed during sparging and concentrations that may be observed weeks or months after groundwater sparging. Groundwater samples should never be collected during active sparging since air bubbling up through monitoring wells or piezometers will volatilize VOCs and provide low results compared to actual VOC concentrations in the formation. In addition, rebound of dissolved-phase VOCs after termination of groundwater sparging is well documented (see Figure 5.2).

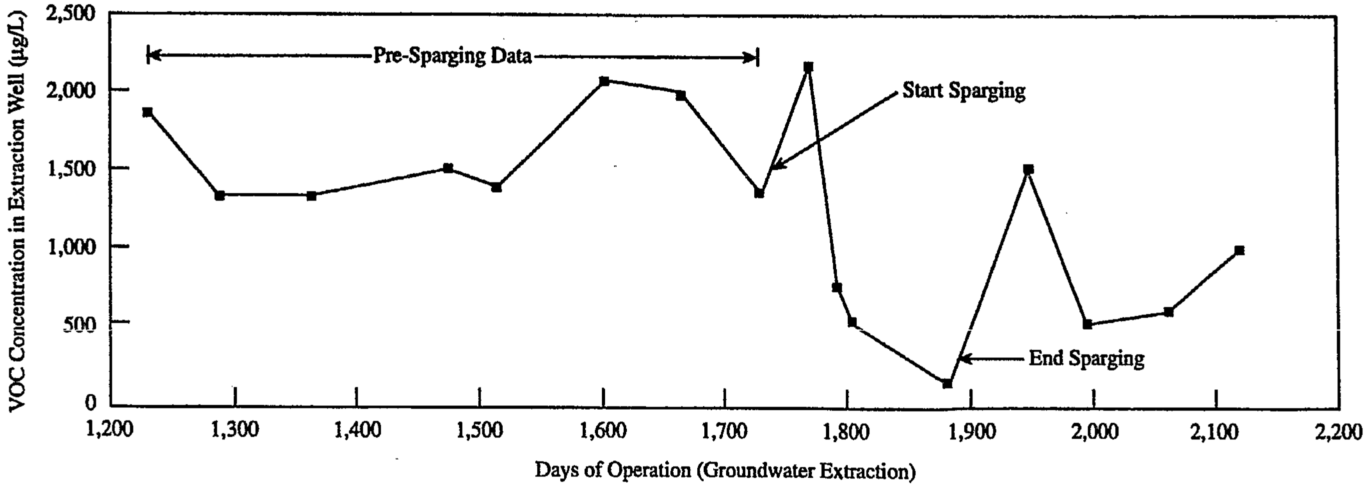
Figure 5.1
Change in Dissolved-Phase PCE During/After Sparging



● PZ-1S
○ PZ-1D
■ PZ-2S
□ PZ-2D

Reprinted from *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes,* P.M. Boersma, K.R. Piontek, and P.A.B. Newman, "Sparging effectiveness for groundwater restoration", pp 39-46, 1995 with permission of Battelle Press.

Figure 5.2
Change in Dissolved-Phase VOCs During/After Sparging



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Rebound is generally from residual NAPL or adsorbed-phase VOCs that continue to partition to the groundwater after sparging is stopped. This phenomena is further documented in studies by Bass and Brown (1997). Ideally, monitoring of sparging system performance should continue for at least four quarters after termination of groundwater sparging. Section 6.4 presents a more inclusive overview on monitoring groundwater sparging systems.

5.1.4 Achievable Groundwater Treatment Clean-up Concentrations

There is little consensus on what concentrations are achievable with groundwater sparging. However, the following serve as general guidelines:

- For favorable sparging sites (uniform sandy material) with only dissolved-phase plumes, reductions in dissolved-phase VOC concentrations from the low ppm to the low ppb range are realistic.
- Sparging systems have been successfully used as cut-off wells at many sites.
- For dissolved-phase plumes in more geologically complex sites, it is possible to reduce concentrations from the low ppm range to the low ppb range, but the chances of success are considerably less, and there is a high likelihood that operational and design changes will be required during the project. There are few, reliable predictive tools that suggest when to expect failure and when to expect success.
- For sites with residual LNAPL, there are few data available to suggest that MCL drinking water levels can be met. Sparging is effective at removing some residual NAPL and even reducing the amount of continuous (floating) LNAPL. As a result, sparging can shrink some plumes and reduce overall concentrations. However, there has not been sufficient soil and groundwater sampling at these sites throughout the groundwater and smear zone with the statistical rigor required to prove that MCL-level concentrations can be achieved.

At this time, it is impractical to predict with certainty whether a particular sparging system will be successful and how long it will take for such a system to achieve success. Much of the research into air sparging, both in the laboratory and in the field, suggests that sparging should rarely work because air flow is channeled along preferential pathways. On the other hand, examples of full-scale sparging systems that have achieved significant and permanent reductions in groundwater concentrations abound. It is likely that hundreds of sparging sites have achieved closure at this time.

Some success and failures of air sparging systems have been documented by Bass and Brown (1997) who compiled a database of about 40 completed in-situ air sparging sites where groundwater contaminant concentrations were compared before sparging was initiated, just before sparging was terminated, and in the months following shutdown of the system. The case studies included both chlorinated solvent and petroleum hydrocarbon contamination and covered a wide range of soil conditions and sparging system parameters. No absolute predictive indicators for sparging success were obvious from review of this database, but some general trends were evident. Air sparging systems achieved a substantial and permanent decrease in groundwater concentrations at sites with both chlorinated and petroleum contamination, both sandy and silty soils, and both continuous- and pulsed-flow sparging. However, in other cases, particularly at sites contaminated with petroleum hydrocarbons, groundwater concentrations either did not decrease during sparging or rebounded significantly after the sparging system was terminated. When sparging was successful at petroleum sites, the permanent reductions in groundwater concentrations were much greater than at chlorinated sites. Poor sparging performance at petroleum-contaminated sites was more likely when high initial groundwater contamination levels suggested a substantial smear zone of residual NAPL. The best sparging performance at petroleum sites was generally associated with a high density of sparging wells addressing the entire source area, a high sparging air injection rate, and a stable water table.

It is necessary to balance these observations with the site clean-up goals. For example, a required 99% reduction of dissolved-phase VOCs at a site with favorable sparging conditions may have the same chance for success as a required 50% reduction in concentrations at a site with less favorable conditions. Sparging at a site with some residual LNAPL may not achieve MCLs in the groundwater, but may result in significant mass reduction and meet a requirement to address LNAPL. Sparging needs to be evaluated at each site in the context of regulatory requirements, site-specific features, and implications for partial or total failure.

5.2 Design Basis

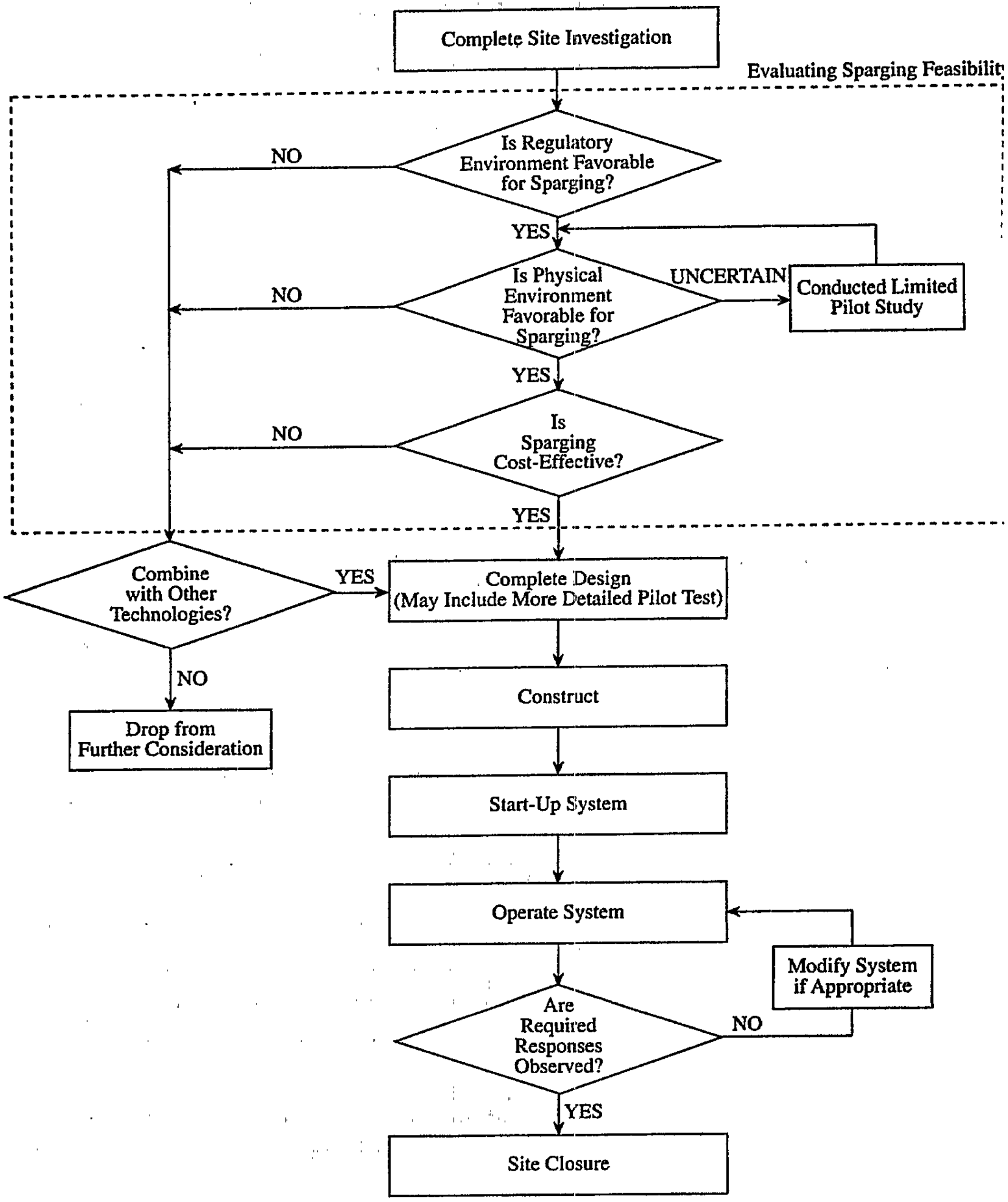
The design basis for sparging systems is fundamentally different than that for vapor extraction/bioventing. There is no practical method by which field measurements can be incorporated into standard gas flow equations for porous media to predict system performance as with vapor extraction/bioventing. Actual air distribution is dictated by pore-scale variations in soil particle size, packing, and permeability that cannot be practically modeled from site information; the design process needs to account for these inherent uncertainties. Therefore, it is necessary to rely on a more observational approach, where systems are installed, operated, and modified as required. This section presents site data required for full-scale design. Figure 5.3 presents an overview of the sparging design/implementation process.

5.2.1 Site and Contaminant Characteristics

Evaluation of the following site parameters is necessary for system design.

- *Soil Characteristics and Stratigraphy.* Low-permeability soils (hydraulic conductivities less than 10^{-5} cm/s) are often unsuitable for air sparging since the pressures required to force sparging air into the formation generally will fracture the soil, producing preferential pathways. Continuous, low-permeability lenses (of even modest thickness) within higher permeability formations, can result in lateral diversion of sparging air. This can leave some areas of the site unaffected by sparging. Continuous strata of substantial thickness within the saturated zone are a significant limitation for air sparging. Consequently, adequate delineation of soil stratigraphy via continuous logging of multiple soil borings is critical to the design process.
- *Depth to Groundwater and Range of Fluctuation.* In most cases, sufficient vadose zone thickness (at least 1 m [3 ft]) must be present to allow for operation of vapor extraction to recover the sparged air, or for biodegradation of volatilized contaminants to be essentially complete before the sparging air exits to the ground surface. Water table variations, both seasonal and during sparging transients, affect not only the design of the vapor extraction wells but also the thickness of the smear zone that forms when the contaminant reaches the water table as a separate phase.

Figure 5.3
Overview of Sparging Evaluation and Implementation



Source: Boersma, Newman, and Piontek 1994

- *Saturated Zone Thickness.* The extent of lateral movement of sparging air is determined in part by the depth of the well seal (or of the top of the well screen if the well is driven) below the water table surface. If the saturated zone is significantly less than 2 m (6.5 ft) thick, it may be difficult for a sparging well to attain significant lateral influence.
- *Pressure/Flow Response.* The flow achieved in response to an applied pressure determines how much air can be delivered to the subsurface to effect remediation and hence places constraints on the sparging compressor sizing. The sparging pressure must not exceed the soil column pressure or fracturing of the soil may occur. Excessive pressure may also result in upwelling during startup, which can render the vapor extraction system temporarily inoperable.
- *Evidence of Vertical Air Movement into the Vadose Zone.* Determined by a pilot test, this is by far the most important information for air sparging that can be gained from site investigation.
- *Evidence of Lateral Air Movement into the Saturated Zone.* The lateral influence of sparging is difficult to measure, and is rarely radially symmetric. Therefore, the term "radius of influence" can be misleading. However, it is important to identify and measure some lateral effect during pilot testing to ensure that the movement of air into the vadose zone is not the result of a poor sparging well seal.

A pilot test providing the above information need not require more than a day in the field to perform. For most smaller sites, this will be sufficient, but extended testing, spanning a few months, may be considered if the size of the envisioned full-scale system is very large. In this case, it is advisable to operate a few sparging wells for an extended period to ensure that substantial and permanent reduction in groundwater concentrations can, in fact, be effected before a large investment is made in an extensive sparging system.

The contaminant properties that most affect sparging feasibility include volatility, aqueous solubility, and biodegradability. The first two determine the contaminant partitioning and hence the thermodynamic driving force for the contaminant to enter the sparged air. For many contaminants of concern these parameters are well known. However, many petroleum products and mixed organic wastes consist of components with a wide range of physical properties. Laboratory analysis of soil or NAPL samples is often used determine the distribution of physical properties.

The concentration of contaminants in the soil and the total mass of contaminants released can also have a profound impact on the effectiveness of air sparging. Dissolved plumes are remediated much more quickly and with wider well spacing than source areas with extensive residual NAPL in a smear zone. Unfortunately, the precise location and total mass of residual NAPL is never known and cannot be reliably estimated from site soil, soil gas, or groundwater analytical data. One approach to dealing with this uncertainty is to install a sparging system initially with wider well spacings, then fill in where groundwater concentrations do not show adequate response. In this approach, the sparging system is used as both a remediation system and a diagnostic tool to find areas of high residual NAPL.

Several additional parameters are sometimes measured through laboratory analysis of soil samples. (If soils samples are collected, each major stratigraphic unit between the seasonal high water table elevation and the elevation of the sparging screen should be sampled.) Organic carbon content affects contaminant partitioning and high levels, such as those typically found in peat, can significantly compromise the effectiveness of vapor extraction on contaminants that adsorb to organic matter. Moisture content (measured in the field via neutron probe or in the laboratory) and the soil moisture retention curve (from an undisturbed soil sample) may be useful in determining the dynamics of air entry into the soil. Other soil parameters sometimes measured include pneumatic and hydraulic conductivity, grain size distribution, bulk density, and porosity. While all of these parameters are often of scientific interest and enhance understanding of the site, at this time they are rarely considered for the initial design basis, but can be used in modeling efforts to track the progress of remedial efforts.

When bioremediation is anticipated to be a significant contributor to remediation, nutrients in soil and groundwater (nitrogen and phosphorous concentrations and speciation and pH) can be measured to ascertain whether nutrient addition will be required. Biological and chemical oxygen demand (BOD and COD, respectively), sulfur and iron concentrations and speciation, dissolved oxygen, and redox potential also can be measured to shed light on the oxygen requirements for bioremediation. In addition, soil bacteria populations can be assessed in the laboratory to evaluate the viability of bioventing, although they are more commonly evaluated through an in situ respirometry test in which biological activity is determined from changes in dissolved oxygen or subsurface temperature during and following sparging system operation.

5.2.2 Pilot Testing

Currently, since there is no known reliably consistent relationship between the transport of injected air into saturated porous media and the resulting air flow distribution and contaminant mass transfer, pilot testing is needed to assess the feasibility of using air sparging at a site. Thus, the primary objective for pilot testing is to assess the basic feasibility of sparging at a site by looking for failures. The most common of these is when air does not exit the saturated zone in the vicinity of the sparging well. Another common failure at low-permeability sites is the inability to induce air flow without fracturing the soil.

A common objective of pilot tests is to assess the zone of influence around a sparging well. *Zone of influence* can be defined as a volume of saturated soil around a sparging well where air flow can be detected or where the effects of air contact, groundwater mixing, or groundwater oxygenation are detectable. This zone is usually estimated by one or more measurements during pilot testing. It should be noted that given the variation in treatment effectiveness within a region influenced by sparging, the term "radius of influence" (ROI) is misleading, and that the term zone of influence represents a better conceptual understanding of this design parameter. As discussed later in this chapter, the ability to measure the zone of influence with commonly employed field observation methods is limited.

Sufficient time is typically unavailable to evaluate fate and transport removal rates during pilot tests. Pilot tests of air sparging technology reported in an American Petroleum Institute database (American Petroleum Institute 1995) were usually less than one day in duration. In that time period, significant improvements in groundwater quality were not observed. In addition, the database indicated that due to the limitations of the monitoring techniques most frequently used in pilot testing, the outcome of pilot-scale evaluations with regard to well spacing was an estimate of ROI rather than zone of influence. Unfortunately, this provides the engineer with only the most simplistic understanding of air flow.

In addition to zone of influence monitoring, the other objectives of pilot testing are to determine the optimal injection pressures and flow rates and to evaluate offgas handling options, contaminant volatilization to the vadose zone, need for offgas treatment, amount of groundwater mounding, and amount of induced vadose zone biodegradation. These criterian are discussed in the following sections. Table 5.1 summarizes pilot test objectives and the relative certainty that a pilot test will meet the objectives.

Table 5.1
Sparging Pilot Test Objectives

Pilot Test Objective	Data Required to Meet Objective	Relative Certainty that Pilot Test Will Meet Objective
Air entry pressure	Flow/pressure relationship at sparging well	High
Duration of groundwater mounding	Frequent groundwater level measurements around sparging well	High
Optimal flow rates	Relationship of flow to dissolved oxygen and dissolved contaminant concentration changes	Low — little rational basis to determine optimum flows. Upper limit on flow is point where matrix fracturing takes place.
Decrease in dissolved-phase contaminants	Analysis of groundwater samples	Moderate/High — several-week pilot test duration required.
Need for SVE system to control vapor-phase contaminants in vadose zone	Contaminant concentrations in soil gas, soil gas pressure resulting from sparging, receptor locations	Moderate/High
Amount of induced vadose zone biodegradation	Oxygen uptake studies before and after sparging	Moderate
Optimal sparging well spacing	All of the above	Low — difficult to determine actual vertical/horizontal air distribution. May vary significantly among sparge wells at some sites.

Source: Boersma, Newman, and Piontek 1994

5.2.2.1 Pilot Test Setup

This section provides general guidance for the basic equipment that is typically used in air sparging pilot tests. For additional information, refer to American Petroleum Institute (1995) and Wisconsin Department of Natural Resources (1993).

The typical pilot test setup includes one or more injection wells, at least two monitoring piezometers, an injection pump, blower or compressor, and ancillary equipment that may include a pressure relief valve, an inlet filter, a flow control valve, and flow meter(s)(Figure 5.4). Provisions must be made for monitoring the pressure, flow rate, and temperature at the wellhead of each injection well. The ultimate fate of the pilot test components should be considered during the selection process, including whether the main components could potentially be used in the full-scale system.

Section 5.3 presents information concerning selection of air sparging equipment for full-scale systems; however, this information is also pertinent to choosing pilot system equipment.

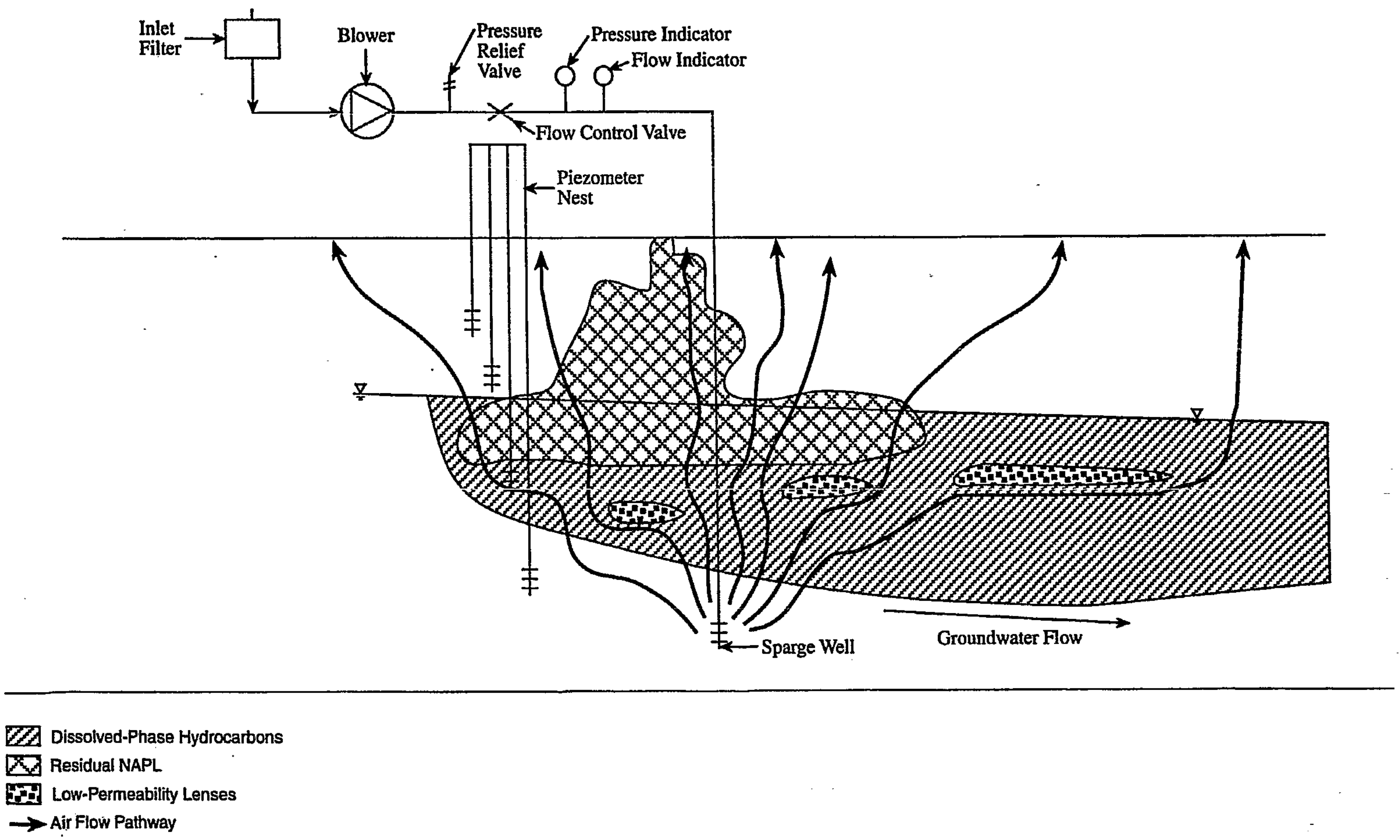
5.2.2.2 Zone of Influence Monitoring

This section discusses available methods for estimating the zone of influence of an air sparging well(s) during pilot testing.

Dissolved Oxygen Measurement. Increased dissolved oxygen (DO) concentrations are often observed in monitoring wells and piezometers during sparging. American Petroleum Institute (1995) indicates that DO monitoring is the most common method of determining the zone of influence of a sparging application. In addition, monitoring of DO during biosparging is critical to understanding the rate of aerobic biodegradation that occurs as remediation proceeds.

Johnson et al. (1995) and Boersma, Piontek, and Newman (1995) demonstrated that the interpretation of sparging effectiveness is dependent on the monitoring strategy employed, especially with regard to the length of screened intervals. Johnson et al. (1995) reported that during short-term pilot testing, DO and the tracer gas helium concentrations in conventional monitoring wells rose, suggesting a broad, and fairly uniform, saturated zone air distribution profile with evidence of injected air having traveled substantial distances (18 m [60 ft]) from the sparging well. However, discrete implants (15 cm [6 in.]) indicated little oxygen and helium transfer in the

Figure 5.4
Conceptual Sparging System



Source: Boersma, Newman, and Piontek 1994

saturated zone, suggesting at best sporadic saturated zone air distribution and limited usefulness of sparging at that particular site. It is likely that wells with long screened intervals had a greater probability of intersecting air channels, and lack of an increase in DO and helium in implants indicated that air channels were not homogeneously distributed. Helium was detected in only two vadose zone implants, again suggesting that air channel formation was erratic. Also, even when a vapor extraction rate was greater than the air injection rate by a factor of 5, only about 50% of the injected helium was recovered by the vapor extraction system, yet again suggesting lack of control in air channel propagation. A monitoring strategy using conventional monitoring wells is much more common and thus likely gives an overly optimistic picture of sparging effectiveness at many sites.

Within a monitoring well, obtaining reliable DO measurements of groundwater that are representative of the aquifer DO concentrations can be a difficult task. Often the very act of collecting a sample can result in aeration and an overestimation of DO. For this reason, it is recommended that at least two methods of DO measurement be used when possible.

The most common methods available for determination of DO in the field are (1) use of a down-hole oxygen probe/oxygen meter, (2) use of an oxygen probe/meter to analyze a sample that has been bailed or pumped from a well, and (3) titration of a sample that has been pumped or bailed. Down-hole probes are easy to use provided the target measurement depth is reachable with the probe connection. Care should be taken to purge the well before taking a down-hole DO reading. In addition, it is common to see significant drift in readings as the probe is moved (even slightly) within the well or even when the probe remains stationary. A standard measurement procedure should be used at each well so that all readings will be comparable. Also, it is important to calibrate the probe/meter often and within the expected temperature range of the aquifer.

When collecting a groundwater sample for analysis, aeration of the sample should be minimized. A peristaltic pump can be used if the sample depth is shallow and use of the pump will not introduce oxygen to the sample. Use of bailers should be avoided if possible.

Titration of a sample using the Winkler method can produce repeatable DO results. The titration process can be greatly simplified by using a field titration method such as the one manufactured by Hach.

Monitoring Well Bubbling. Monitoring wells located near sparging wells often experience bubbling. Bubble formation in monitoring wells is likely caused by air channels intercepting the well bore, allowing air to rise vertically through the well. If the monitoring well is sealed, local transient mounding and subsequent propagation of air channels should occur. Therefore, a well with air flow or bubbling should be sealed. Also, samples do not provide useful information when collected from wells experiencing bubbling for DO and VOC analysis — the wells are effectively operating as an air stripper and there are not representative of the groundwater in the formation.

Neutron Moisture/Density Probes. A neutron moisture probe is a field instrument that can be used to estimate changes in soil water saturation due to the effects of air sparging. The probe contains a "fast" radioactive neutron source and a "slow" neutron detector (Acomb et al. 1996). The probe is typically lowered down an access pipe and a cloud of fast neutrons is released into the surrounding soils. The neutrons collide with hydrogen atoms, thereby slowing or thermalizing the neutrons. The slow neutrons are then counted by the neutron detector, and the results are converted to an estimate of soil saturation based on baseline measurements for 100% and 0% saturation. Unfortunately, the probe measures hydrogen, which can be found in either water or contaminants. Therefore, it is difficult to differentiate water saturation from contaminant saturation.

Neutron probes have been used for over 50 years and have been commercially available for more than 35 years. The technology is well established in the agricultural, environmental, and petroleum and gas industries. Neutron probes offer a precise, inexpensive (about $5,000), nondestructive, and real-time method of monitoring relative saturation. The probes are also fairly easy to use. Newer designs are highly automated with computer control of measurements and data collection.

Acomb et al. (1996) recently published neutron probe results from an air sparging site characterized by uniform "beach sand" and contaminated with gasoline and diesel range hydrocarbons. They found measurable air distribution in previously water-saturated soil at 3.5 m (12 ft) from the air sparging well. The air distribution was found to stabilize within 12 hours of sparging startup. Further, the results indicated that frequent pulsing is needed to optimize air transport with subsequent groundwater mixing.

Time Domain Reflectometry (TDR). TDR measures soil moisture content by propagation of electromagnetic pulses along a pair of transmission waveguides in direct contact with the soil. TDR offers precise measurement of soil moisture content because the dielectric constant for dry soil particles differs so much from that of water (Topp, Zegelin, and White 1994). TDR systems have been used to monitor air sparging systems by Clayton, Brown, and Bass (1995) by pushing a pair of waveguides (a probe) into the bottom of a soil boring to a known depth and backfilling above the probe with grout. TDR is a well-established technology that provides real-time moisture and time series measurements that can be procured commercially.

Electrical Resistivity Tomography (ERT). ERT is a technique for surveying the two-dimensional electrical conductivity of the subsurface between wells spaced 1.5 to 7.5 m (5 to 25 ft) apart (Lundegard, Chaffee, and LeBrecque 1996). Conductivity is directly related to water saturation. Therefore, this technology can be used to determine the percent air saturation extending outward from an injection well. The method has been used in air sparging research but has had little use in pilot tests to date.

Tracer Gas Tests. Tracer gas tests use gases not naturally occurring in the subsurface of a site, such as sulfur hexafluoride or helium, to indicate rates and/or patterns of injected air flow. The advantage of using tracer gases is that, unlike oxygen, they are conservative and not depleted by geochemical or biological reactions. During the pilot test, the tracer gas is injected directly into the injection airstream. Required equipment includes a tracer gas cylinder, pressure regulator, flow meter, piping to the injection point, a sample pump, and a tracer gas detector. Soil gas and groundwater is monitored for the tracer gas at discrete saturated zone monitoring points to define the distribution at various times during sparging. Tracer tests can be valuable in clarifying uncertainty about uncontrolled VOC emissions to exposure points.

Groundwater Mounding. Mounding, simply defined, is the observation of elevated water levels in monitoring wells and piezometers during sparging. If the water table is close to the surface, water level rise can become fairly dramatic as some wells may become “artesian” (i.e., water flows freely from wells). Mounding can be described as a multistage process. The first stage is characterized by a period of vertical and radial displacement of groundwater with pressurized air. During this time, the rate of air injection into the saturated zone exceeds the rate of air flow out of the saturated zone resulting in pressure buildup and thus elevated water levels in piezometers and monitoring wells. Elevated pressure during this stage allows initial formation of air channels or zones of desaturation. Numerical, multiphased modeling by Lundegard and Andersen (1996) indicates that in relatively homogeneous media, formation of air channels away from the sparging wells should result in a region of desaturation resembling a teardrop- or bell-shaped geometry. Because the compressibility of water is very low, pressure buildup (mounding) propagates a far greater distance than the region of air flow. Thus, the use of mounding as an indicator of the zone of influence typically results in an overestimation of the region of air flow. In an unconfined aquifer, some portion of mounding manifested by water level rise in piezometers is likely due to actual physical elevation in the water table in addition to a pressure response.

When the significant air flow finally breaks through to the vadose zone, pressure is released since the air flux out of the saturated zone is greater than the air flux into the saturated zone and mounding dissipates. Decrease in pressure results in collapse of air channels more radially distant from the sparging well, and air flow is confined to regions of higher permeability near the sparging well. During this period, groundwater flow back toward the sparging well would be expected. Thus, the radial extent of air flow actually decreases as steady-state conditions are approached. Lundegard and Andersen's (1993) numerical simulations indicate that when air breaks through to the vadose zone, the region of desaturation resembles a conical shape. When steady-stage conditions are reached, little or no mounding exists. Thus, the importance of achieving steady-state conditions during sparging testing becomes apparent in that transient or short-term testing will likely result in overestimation of the region of air flow. After achievement of steady-state conditions, a persistent water level elevation may be observed hydraulically upgradient of sparging wells due to diversion of groundwater flow. Displacement of groundwater and creation of a zone of desaturation during sparging may create a region of limited lateral groundwater flow due to lowered conductivity.

The relationship between groundwater mounding and displacement of the dissolved-phase plume or displacement of continuous NAPL has been the subject of much debate. It is unlikely that continuous NAPL is displaced by temporary groundwater mounding. The NAPL may be submerged during the groundwater mounding, and there may be some mixing of the NAPL as the groundwater subsides, but there does not appear to be significant horizontal displacement of continuous NAPL. Fears that continuous NAPL may "slide down" the groundwater mound are unfounded. There is some displacement of the groundwater and hence the dissolved-phase plume. Simple groundwater flow calculations of the magnitude of temporary horizontal and vertical gradients induced by sparging and the duration of those gradients suggest that groundwater displacement is on the order of millimeters to inches, but not several feet per sparging cycle (Boersma, Piontek, and Newman 1995). While the displacement would not be sufficient to result in large-scale plume displacement, the groundwater movement may result in added mass removal since each sparging cycle results in varied groundwater distribution in relation to the air channels, which remain fixed. In this way, sparging is more effective in dissolved-phase plumes than residual NAPL since dissolved-phase contaminants may eventually come in contact with an air channel due to displacement, while residual NAPL is fixed in the soil pore and may not be removed if it is not directly contacted by an air channel (Boersma, Piontek, and Newman 1995).

Given this description of the dynamics of groundwater mounding during air sparging, the importance of monitoring water table elevations during sparging pilot testing should be apparent. In most cases, simple groundwater level probes are sufficient. For more complex sites or where more accurate readings are needed, or in wells where bubbling (from nearby sparge wells) is expected, pressure transducers with data loggers can be used.

5.2.2.3 Step Test Procedures

An air injection step test may be conducted during the pilot testing using a procedure similar to the vapor extraction step test described in Section 3.2.2.1. The recommended sequence is:

1. Open the air outlet valve, which discharges compressed air to the atmosphere.
2. Close the valve leading to the wellhead.
3. Turn on the blower so that air is being forced out through only the air outlet valve.
4. Fully open the valve leading to the wellhead.
5. In a series of increments, slowly close the air outlet valve.
6. For each increment, allow the flow rate to stabilize and record the wellhead pressure and flow rate into the sparging well.

No flow will be measured until the minimum pressure required to initiate flow is exceeded. Record the pressure at which flow is first initiated.

7. Continue closing the outlet valve until the desired flow rate is achieved.

Step test results generally fall under one of the following three scenarios with regard to how injected air is transported in the formation (Baker, Pemmireddy, and McKay 1996):

1. Air flow commences at, or very close to, the hydrostatic pressure (the pressure required to push the water within the well down to the top of the screen interval). This suggests that the air entry pressure (the pressure required to force air into the formation) is small and that air flow is occurring primarily within large pores. Air flow may be well distributed in this case if uniform sands are present; however, if the soils are heterogeneous, preferential flow via the most permeable pathways is likely.
2. Air flow does not occur until a pressure greater than the hydrostatic pressure is applied, indicating that the well screen did not intersect macropores or high-permeability lenses. Air flow in this case may be well distributed if the formation consists of uniform fine sands or silts.
3. No significant air flow is measured even when the injection pressure is increased to 0.8 of the overburden pressure (the pressure due to the weight of the soil and groundwater above the top of the screen). In this case, the sparging screen is located within a low-permeability zone of soil and the well should be depressurized since there is a risk of pneumatically fracturing the formation.

When conducting sparging pilot tests, both pressure and flow rate need to be monitored and controlled. Varying pressure, so that it is the independent variable, will allow the operator to achieve the desired flow rate. However, it is ultimately flow that needs to be controlled in a pilot- or full-scale application.

5.2.3 Pilot Test Result Interpretation

5.2.3.1 Vertical Air Movement into the Vadose Zone

The principal function of a sparging pilot test is to ascertain if sparging is feasible, i.e., whether sparged air is reaching the vadose zone. The surest way to determine vertical air movement is to inject a tracer into the sparging air during pilot testing and analyze the vapor extraction offgas for the tracer. Helium (He) and sulfur hexafluoride (SF_6) are the most commonly used tracers. Helium is inexpensive and easy to identify using a field thermal conductivity detector, but the detector is not very sensitive (detection limits for helium using a typical field helium detector are 0.01% to 0.1% by volume). Hydrogen, which can be present in highly-reducing environments due to microbial activity, can interfere with helium detection. For these reasons, SF_6 is usually a better choice as a tracer. A field gas chromatograph equipped with an electron capture detector can accurately detect SF_6 at levels less than 1 ppb_v.

The tracer gas can be either injected all at once or continuously bled into the sparging air. Monitoring offgas or soil vapor after injection of a slug of tracer provides the impulse response of the system. If the tracer gas is observed in the vapor extraction offgas within a few minutes, the sparging air has moved vertically unimpeded into the vadose zone. If the time until tracer is first detected is on the order of an hour or more, the sparging air has traveled largely laterally for some distance before finding a path to the vadose zone. Radial air flow models can be used to estimate transit time to the vapor extraction well as a function of distance from the well; this would represent the upper bound of the distance the air from the sparging air would have had to travel before reaching the vadose zone. If a monitoring well penetrating deep into the saturated zone is present within this distance, it may be that the monitoring well is providing a preferential pathway through an impermeable barrier, and the results of the test should not be viewed as unequivocally positive.

Tracer slug tests can also be used to perform a mass balance between tracer injection in the sparging air and tracer recovery in the vapor extraction offgas. However, there is always some retardation of tracer in the saturated zone through sorption and retention of air. For mass balance calculations, it is usually better to bleed tracer into the sparging air continuously at a known mass rate. The sparging system is then operated continuously and the vapor extraction offgas monitored for tracer gas until steady-state conditions are reached. A mass balance is performed by comparing the rate of tracer flow into and out of the subsurface.

For any mass balance calculation, it is crucial that the vapor extraction system is recovering all soil gas within the anticipated zone of sparging influence. This may mean operating the vapor extraction system at a flow rate much higher than the air sparging rate, sealing the ground surface to minimize air infiltration, and/or operating more than one vapor extraction well during the test.

When a tracer test cannot be performed, evidence of sparging air reaching the vadose zone can be found from monitoring the vapor extraction offgas for volatile contaminant vapors. Typically, the VOC concentrations in vapor extraction offgas will reach a steady-state value after a few pore volume exchanges in the vadose zone. If a sparging system is turned on after these steady-state conditions have been established, then the VOC concentrations in the vapor extraction offgas will suddenly increase provided the sparged air is reaching the vadose zone. This is a less definitive determination than a tracer test, but it is also less susceptible to false positive results when there is a poor seal on the sparging well. In this case, tracers would readily enter the vadose zone through the failed well seal, but the vadose zone VOC levels would not be significantly affected since the sparging air would be passing through clean well gravel.

Evidence can also be found for sparging air reaching the vadose zone when doing pilot tests without vapor extraction. Observation of positive pressure in the vadose zone is evidence that sparging air is entering the vadose zone, especially if the positive pressure dissipates with distance from the sparging well. It is necessary to perform background vadose zone pressure measurements when applying this technique, especially when the depth to groundwater is large, to ensure that barometric pressure fluctuations are not producing false positives.

5.2.3.2 Lateral Air Movement into the Saturated Zone

It is important to identify some lateral effect during pilot testing to ensure that the movement of air into the vadose zone is not the result of a bad sparging well seal. If a tracer gas has been injected with the sparging air, the observation of the tracer in groundwater in a monitoring well or piezometer is unequivocal evidence that the sparged air has moved laterally through the saturated zone.

The observation of bubbling in a monitoring well obviously means sparged air has reached the monitoring well through the saturated zone. High pressure in a monitoring well is also strong evidence that sparging air is reaching the well through the saturated zone. This is particularly true if the monitoring point is occluded, i.e., screened exclusively below the water table. When this is the case, there are no plausible means by which air could enter the well except through the saturated zone. When measuring pressures on an occluded monitoring well, it is always necessary to vent the well briefly before applying the pressure measurement device so that a water table rise is not misinterpreted as pressurization of the monitoring well by sparged air.

Large increases in VOC concentrations in the headspace of a monitoring well screened across the water table are sometimes taken as evidence that sparged air has reached the monitoring well through the saturated zone. Increases in dissolved oxygen levels in the monitoring wells often are interpreted in this way as well. However, dissolved oxygen can be difficult to measure reliably using a field probe since disturbing the monitoring well can change the apparent dissolved oxygen level. Various methods to obtain more reliable dissolved oxygen information have been explored, including (1) continuous pumping of the well; (2) installation of galvanic oxygen monitors directly in the saturated zone; and (3) lowering evacuated ampules containing a reagent into a well, breaking the ampule tip remotely, and analyzing the recovered water standards colorimetrically.

5.2.3.3 Pressure/Flow Response

The flow achieved in response to an applied pressure is a key parameter in sparging system design as it determines the appropriate sparging compressor or blower sizing. The pressure/flow response also lends insight into the nature of sparging air movement through the subsurface and may be useful in assessing the potential efficacy of a sparging system.

Sparging air flow does not commence until sparging pressure exceeds a threshold pressure, consisting of the sum of the hydrostatic pressure and the air entry pressure through the filter pack (if present) and the formation. Hydrostatic pressure is expressed as

$$P_h = \rho_w g \Delta z \tag{5.1}$$

where: P_h = hydrostatic pressure;
ρ_w = density of water;
g = acceleration of gravity (9.81 m/s^2 or 32.17 ft/s^2 at mean sea level); and
z = distance from static groundwater surface to top of the sparging well screen.

Air entry pressures, which can range from a few centimeters water column or less in coarse sands and gravels to more than a meter water column in silts, are represented by:

$$P_e = \frac{4\sigma}{d} \tag{5.2}$$

where: P_e = air entry pressure;
σ = surface tension of water in air; and
d = diameter of constrictions along the largest pores of entry.

Sustained air flow requires that air not only enter individual pores but also form continuous channels through the entire formation. This occurs at the inflection point of a Van Genuchten curve fitted to the soil moisture retention data. The inflation pressure (P_{infl}) is a slightly higher pressure than P_e. Once sustained flow is achieved, friction in the sparging well casing will contribute to pressure loss. The Manning (or Darcy) equation for head loss due to friction of a fluid moving through a cylindrical pipe is generally used, provided the density of the sparging air does not change substantially (due to pressure and temperature changes) within the sparging well riser. The diameter of the sparging well should always be sufficient to ensure that, at the flow rate and sparging depth required, the frictional losses are negligible.

As sparging pressure increases above that necessary to sustain air flow, more and more air will flow through the formation creating channels through smaller and smaller pores. However, at the point where the applied pressure exceeds the weight of the soil column above it, the soil may fracture, and the resulting large channels will serve as preferential pathways for sparging air. Optimum sparging pressure is therefore the highest pressure achievable without risking soil fracturing (Wisconsin Department of Natural Resources 1993).

To estimate the maximum operating pressure (i.e., a function of the weight of the soil and water column above the top of screen), the following simplistic example is provided (Wisconsin Department of Natural Resources 1993) which assumes a:

- soil specific gravity of 2.7;
- water table depth of 5.5 m (18 ft);
- sparging well screened from 9.1 to 10.7 m (30 to 35 feet);
- porosity of 30%; and
- homogeneous, isotropic, and unconsolidated soils.

Using English-system units for illustration, the overlying pressure exerted by the weight of the soil column:

$$\text{Weight of soil per square foot} = 30 \text{ ft} \bullet 2.7 \bullet (1 - 0.3) \bullet 62.4 \text{ lbs / ft}^3 = 3{,}538 \text{ lbs / ft}^2$$

$$\text{Weight of water per square foot} = (30 - 18)\text{ft} \bullet 0.3 \bullet 62.4 \text{ lbs / ft}^3 = 224 \text{ lbs / ft}^2$$

$$\text{Total} = 3{,}538 + 224 = 3{,}762 \text{ lbs / ft}^2 \bullet 1 \text{ ft}^2 / 144 \text{ in}^2 = 26 \text{ psig at 30 feet of depth}$$

In this example, injection pressures greater than 179 kPa (26 psig) could cause system problems and secondary permeability channels to develop. Therefore, as with all designs, a factor of safety should be used equivalent to 60-80% of the overlying pressure (i.e., 107-143 kPa or [15.6-20.8 psig] for this example). Engineers must remember that each site has specific conditions and requirements and should use all available information when performing these calculations.

Using the calculated pressure data along with pilot test data, the pressure necessary to deliver the desired air flow rate under all seasonal operating conditions can be calculated. Professional judgment is required to determine design pressures and flow rates for each sparging well. If an air flow rate of 0.5 scfm per well cannot be maintained at the site, the soil permeability may be too low and air sparging may not be appropriate for the site.

In some cases, the apparent rise in groundwater table that occurs when sparging is initiated may limit sparging air pressure to levels below the recommended maximum based on soil fracturing considerations. In situations where the depth to groundwater is relatively shallow (less than 3 m [10 ft]), and especially where the soil permeability is fairly low, upwelling in monitoring wells during startup due to excessive sparging air pressure may be problematic. If the upwelling approaches or exceeds the top of the vapor extraction well screens, the vapor extraction system will be rendered temporarily inoperable due to excessive water entrainment or deadheading of the extraction wells.

5.2.3.4 Biodegradation Rate

Saturated zone in situ respirometry methods have recently been tested at an air sparging site in Ft. Wainwright, Alaska (Gould and Sexton 1996). Microbial uptake of dissolved oxygen in the saturated zone was measured quarterly, and the decrease in dissolved oxygen concentration was attributed to biodegradation of hydrocarbons based on certain assumptions, including soil porosity and zone of influence. Accounting for advective and dispersive fluxes of dissolved oxygen away from the zone of influence following shutdown of the sparging system, as well as the effects of nontarget inorganics such as ferrous ion on oxygen uptake, are limitations of such methods.

An alternative approach to assessing biodegradation rates from sparging operation is to assign temperature rise in the saturated zone to biological activity (Acomb et al. 1996; Veenis, Bass and Bartholomae 1997). Temperature increases in groundwater during air sparging may be as much as 30°C, although they are more commonly in the range of 5 to 10°C. A steady-state heat balance explaining this temperature change is complex. Energy inputs include the heat of biological activity (the variable for which the equation is solved), sensible heat of injected air, latent heat of moisture condensation in injected air, plus various other convective and conductive terms. Energy losses include sensible heat leaving with sparging air and latent heat of evaporation, as well as other convective and conductive terms. The biodegradation rate is calculated from the heat of biological activity, assuming the hydrocarbon is degraded to some proportion of cell mass and carbon dioxide/water. Although many estimations and assumptions are required in the computation of biodegradation rate, the input data (i.e., temperatures in the subsurface as a function of depth) are easy to measure accurately. This approach has been used to provide estimates of bioremediation rates which generally agree with the results of other methods.

5.2.3.5 Rate of Contaminant Volatilization

A final key parameter to monitor during a sparging pilot test is the rate of contaminant volatilization from the groundwater and smear zone. When sparging in only dissolved-phase plumes, the rate of contaminant volatilization is typically low. Vapor-phase contaminant concentrations may remain at only the low ppm or even ppb levels. During the design phase, the mass flux of contaminants being transported into the treatment zone can be estimated from dissolved-phase concentrations and the groundwater flow velocity. Assuming that all of the dissolved-phase VOCs are volatilized, the maximum concentration of vapor-phase contaminants can be estimated. These estimates can be coupled with vapor-phase transport models to assess if active soil gas collection is needed. If the natural attenuation of contaminants occurs at a rate faster than the advective transport of contaminants to some compliance point, active soil gas collection and treatment may not be required. Such estimates and models are useful during pilot test planning and design stages of the project. There is a growing body of literature that suggests significant retardation and biodegradation of vapor-phase contaminants in the root zone of the soil column (Kampbell, Wilson, and Griffin 1992).

When sparging through residual NAPL from petroleum product releases, it is common to observe in situ vapor-phase hydrocarbon concentrations in the percent range (greater than 10,000 ppm); these concentrations are in the explosive range as well. In such cases, soil vapor collection and treatment is almost always required. It is also necessary to consider the risks associated with the uncontrolled migration of potentially explosive vapors to sewers, basements, and other subsurface structures.

5.2.3.6 Biofouling

There has been much speculation about the potential for fouling of the aquifer due to iron precipitation as a result of sparging. The anearobic activity at many sites results in high dissolved-phase iron concentrations in the groundwater. The iron can quickly become oxidized in the presence of air introduced via a sparging system and precipitate out of solution. The sparging guidance published by the Wisconsin Department of Natural Resources in 1993 suggested that iron precipitation may be a problem at iron concentrations greater than 10 mg/L, but also acknowledged some uncertainty with regard to the accuracy of the number. Many more sparging projects have been undertaken since that time, and there is little evidence to suggest that iron precipitation is a concern at most sites.

5.2.4 Preliminary Design

During preliminary design, the final well spacing and layout based on pilot test results or past experience is to be established. As previously discussed, determining the radius of sparging influence for most applications using conventional field measurements is difficult. Arguably, the concept of a radius of influence does not even apply to sparging since sparged air often moves outward from the sparging well in radially asymmetric patterns. Furthermore, it is the density of air fingers and channels that determine the effectiveness of air sparging, not the mere presence of sparged air in the saturated zone. A few channels of air may move a considerable distance in the saturated zone from the injection point, but the region of effective remediation would be considerably smaller.

Rather than basing sparging system design on an elusive radius of influence, a more realistic approach may be to rely on past experience. Bass and Brown (1997) found that, in general, source areas with extensive residual NAPL present in a smear zone responded better to sparging systems with closer well spacings (less than 6 m [20 ft]) and higher sparging air flow rates (greater than 5 scfm). Dissolved plumes responded much more quickly and with much wider well spacings than source zones. Since the precise location and total mass of residual NAPL is never known and cannot be reliably estimated from site soil, soil gas, or groundwater analytical data, it is advisable to install a sparging system initially with wider well spacings, then fill in where groundwater concentrations do not show adequate response.

When the sparging system is used in this way as both a remediation system and as a diagnostic tool to find areas of high residual NAPL, the initial sparging system design will require modification or upgrading after several months to a year of operation. Appropriate flexibility in both design and budgeting are required to ensure the effectiveness of an air sparging application.

5.3 Air Sparging and In Situ Equipment Selection

This section has been adapted with permission from Dupont et al. (1998) and US ACE (1996).

5.3.1 Air Sparging Well Location and Construction

5.3.1.1 General

As discussed at the beginning of this chapter, well system configurations can be designed to accomplish different strategies and may consist of a linear orientation perpendicular to groundwater flow direction (sparging curtain), nested wells (air sparging and vapor extraction from different depths of the same or nearby boreholes), encapsulation of the contaminant plume (surrounding the plume with air sparging wells), and horizontal air sparging wells. When using sparging curtains, care must be taken in both the design and operation to ensure that sufficient contact is achieved between the sparged air and the contaminated groundwater plume passing through the curtain. Additionally, the use of a sparging curtain may result in contaminated groundwater migration around the curtain due to a likely decrease in hydraulic conductivity and increase in upgradient head. Likewise, nested wells and plume encapsulation approaches require care in design and operation. Nested wells have a primarily vertical pressure gradient that can reduce the zone of influence and require special operating schemes. Encapsulation systems must be designed and operated to account for transient groundwater mounding that will occur with the injection of sparging air.

If the selected configuration addresses only a portion of the plume, groundwater extraction is likely to be required to control potential lateral migration. Conversely, if sparging wells extend to the perimeter of the contaminant plume, groundwater extraction wells may not be necessary. A complete understanding of site conditions is required so a configuration can be chosen that will effectively remediate the affected aquifer and fringe areas.

During air sparging system operation, lateral distribution of contaminants in the saturated zone may increase due to new induced groundwater flow patterns. Additional monitoring wells and air sparging wells should be considered for placement near the perimeter of the contaminated zones. Prior to finalizing the well layout, existing utilities must be located, with relocation of air sparging wells or utilities and service requirements for new equipment taken into account as appropriate. Site access, including considerations for support facilities, storage areas, and parking, should also be identified to prevent the potential release or migration of contaminants by installation equipment during construction.

5.3.1.2 Vertical Wells

Most groundwater sparging systems are installed with vertical sparging wells. Typical design parameters are shown in Table 5.2. Sparging wells are typically constructed of PVC or galvanized steel and can be installed through drilling with a hollow-stem auger or driven with a geoprobe. For most applications, it is important to develop the sparging wells before sparging, since fines can accumulate in the bottom of the wells and block the relatively short well screens. When installing wells in varied stratigraphy, conventional drilling and soil logging techniques should be used so there is a record of the geology in the immediate vicinity of the sparging well; this information will help with final screen placement as well as future data interpretation.

Table 5.2
Design Parameters for Air Sparging Systems

Parameter	Typical Range
Well Diameter	2.5 to 10 cm (1 to 4 in.)
Well Screen Length	15 to 300 cm (0.5 to 10 ft)
Well Screen Depth Below Water Table	0.6 to 15 m (2.0 to 50 ft)
Air Sparging Flow Rate	0.08 to 0.5 m^3/min (3 to 20 scfm)
Air Sparging Injection Overpressure*	7 to 70 kPa (1 to 10 psig)
Air Sparging Zone of Influence	1.5 to 7.5 m (5 to 25 ft)

*Overpressure is injection pressure in excess of hydrostatic pressure

Source: US ACE 1996

5.3.1.3 Horizontal Wells

Increasingly, horizontally-drilled wells are used in sparging applications, and horizontal wells placed in excavated trenches are used for sparging barriers. Effective operation of such horizontal vapor extraction systems requires that air flux to the formation be uniform over the length of the well. However, frictional losses can result in the bulk of the air exiting the well at the end nearer the sparging blower.

Several approaches to obtain a constant flux along the length of a horizontal sparging well have been explored. A diffuser pipe with a large pressure drop can be placed within the sparging well along its entire length (Wade 1996). In this case, the pressure drop is so great for air exiting the diffuser pipe that a very high applied pressure is required. The pressure drop along the length of the pipe is therefore negligible in comparison. This approach carries additional expenses for the coaxial diffuser pipes as well as greater blower requirements to deliver air at higher pressures.

Another approach is to vary the depth of the horizontal well installation below the top of groundwater such that the hydraulic head decreases at greater distance from the blower to compensate for the reduced pressure due to frictional losses. Computerized design tools have been developed to predict how the sparging well can be pitched so as to ensure constant air flux along the length of the well (Fournier and Skomsky 1996; McPhee, Bass, and Smith 1997).

While both of these approaches are appealing in theory, long, horizontally-drilled sparging wells are likely to find and inject air preferentially into the most permeable areas of the soil. Reducing the length of the horizontally-drilled wells will reduce the disproportion of air flow, but will also increase installation costs. Therefore, horizontally-drilled wells should be used only to treat source areas and downgradient plumes with soils displaying a high degree of uniformity. Placing horizontal sparging wells in trenches, where the uniformity of the backfill can be ensured, will circumvent this problem, but this approach can only be used in sparging barrier applications.

5.3.2 Field and Manifold Piping

5.3.2.1 General

Figure 5.4, presented earlier, is a schematic diagram that includes a typical air sparging manifold design. The construction of an air sparging manifold generally includes the following components:

- pressure and temperature gauges;
- air flow meters;
- pressure relief valve or bypass line;
- throttle valves;
- manifold piping or hose;
- check valves; and
- optionally, solenoid valves and sample ports.

Each of these components is discussed below. The piping system can be designed for installation either above or below the ground surface depending on the traffic requirements of the area and the need for protection against frost.

5.3.2.2 Design and Installation of the Manifold

Beginning at the outlet of the air supply source (typically a compressor, blower, or gas cylinder), compatible materials are connected to supply headers for the air sparging wells. Typical manifold construction materials include metal piping, rubber hose, or ABS pipe. PVC pipe, although in common use, is not recommended by manufacturers for air pressure service. Prior to routing to individual air sparging wells, permanent pressure and temperature gauges and switches along with an air flow meter are installed for quick visual measurements during routine system checks. The measurement devices are also connected to the electrical supply system in case of system nonconformances to specified operating conditions. These permanent measurement devices should be installed in accordance with the manufacturers' recommendations for length of unobstructed flow, etc. A pressure relief valve (manual or automatic) or system bypass line should be installed to exhaust excess pressure from the manifold. This will prevent excessive pressure, which could cause damage to the manifold or aquifer. Exhaust air can be directed to the atmosphere or to the air source intake. A silencer for exhaust air should be considered based on site conditions and air velocities.

A header from the manifold to each well must be designed. Reasonable construction options for piping materials and associated costs must be evaluated to determine the most effective air delivery system to each sparging well. Once the piping materials are selected, each well should have a throttle valve; check valve; temporary ports for flow, pressure, and temperature measurements; and, optionally, a solenoid valve and sampling port. The throttle valve is used for air flow adjustment or well isolation from the manifold system. Typical throttle valves used are gate, globe, butterfly, or ball valves. Check valves are installed on each well to prevent temporary back pressure in the screened interval of the aquifer from forcing air and water up into the manifold system during system shutdowns. If a check valve is not installed on each well, a single check valve must be located on the manifold line between the permanent instrumentation and the gas pressure source.

One or more ports that can be used for temporary measurements of air flow, pressure, and temperature are recommended to perform system optimization adjustments during operations. Solenoid valves are optional features and their use is dictated by the system operating strategy. If pulsed operation of the system is anticipated for more effective remediation or reduced energy consumption (discussed in detail in 6.4), solenoid valves must be installed for ease of individual well activation and deactivation. Simple analog or PLC timers can be used to actuate the solenoid valves based on specified time intervals. It should be noted that check and solenoid valves may significantly restrict air flow or generate significant line pressure drops. The pressure drop across these appurtenances, if they are used, must be accounted for when sizing manifold piping. Also, all manifold instrumentation should be constructed with quick-connect couplings for ease of maintenance and removal.

The manifold that delivers supplied air to each air sparging well is typically installed underground below the site-specific frost line. If piping is installed in the frost line or aboveground, it may need to be protected from freezing with insulation and/or heat tape. Aboveground installation designs should be reviewed for items such as shock load, photo-oxidation, and potential vehicular damage. All construction including excavation, trench bottom preparation, and backfilling/compaction should be performed in accordance with industry-accepted standards. The manifold sizing is site-specific and dependent on factors, such as air flow rate, pressure losses, material costs, and line distribution patterns. As stated above, although convenient for short-term tests, PVC is not recommended for air pressure service. All piping should be installed in accordance with the manufacturer's recommendations. If rubber hose or ABS pipe is used, the installation should include tracing tape or other appropriate material that can be located with a metal detector, if necessary, after completion of the installation (except at sites where surface or subsurface conditions would prohibit locating efforts, such as reinforced concrete paving or underground lightning grids). Once the manifold has been completed to each well, high-pressure air hose or hard pipe, accompanied with couplings and plugs, can be used to secure the manifold to the well header.

5.3.3 Air Sparging Compressors

5.3.3.1 General

Air delivery sources are designed on (1) design calculations of required minimum pressures due to hydrostatic head, air-entry pressure, and manifold losses and (2) system requirements developed from pilot tests. Upon completion of the total system design calculations and review of pilot test data, the optimum pressure and flow for each well is determined for the site-specific geologic and physical domain. Typically, the air supply is provided by either an air compressor or blower.

Air compressors are typically quite noisy, and if they are to be near residential areas, they should be located in enclosures outfitted with noise abatement equipment and insulation. Air compressors can also generate significant heat; therefore, piping material should be compatible with expected discharge pressures and temperatures. This is often accomplished by using several lengths of metal piping to allow for heat transfer and system cooling before coupling to piping made of polymeric materials.

Air compression leads to the precipitation of water in the compressor receiver tank and manifold lines. Therefore, air tanks should be drained regularly to prevent condensate buildup. It may be necessary to winterize the compressor system and heat trace exposed piping to avoid system icing and blockage.

Continuous-duty, oil-less air compressors are typically used to avoid introducing hydrocarbons to the aquifer. An alternative to oil-less compressors is use of oil filters to remove hydrocarbons from the air stream before it enters the groundwater.

Rotary-vane pumps or regenerative blowers can be used only when low air pressures (i.e., up to 69 kPa [10 psig]) are required. Rotary-lobe blowers can be used for sparging sites when air pressures do not exceed 103.5 kPa (15 psig). Reciprocating compressors are generally required for pressures in excess of 103.5 kPa (15 psig). Reciprocating compressors can generally achieve over 621 kPa (90 psig) pressures and often use Teflon® components to avoid the use of lubricants. Other types of compressors (i.e., rotary screw) can potentially be used if provisions are made to keep hydrocarbon lubricants from entering the air stream.

In all cases, compressor air inlets should be located to avoid the introduction of airborne contaminants. Therefore, inlets should not be located within service garages or in close proximity to vapor extraction stacks.

5.3.3.2 Unit Selection

The first consideration when beginning calculations for operating pressures is to avoid excessive pressures that could cause system malfunctions and/or the creation of secondary permeability in the aquifer. The estimation of minimum and maximum air pressures required for operation begins with the assumption that the pressure must at least equal the pressure head at the top of the well screen plus the air-entry pressure required to overcome capillary forces. For calculating the minimum required system operating pressure, use the common conversion that each foot below the water table equals 2.97 kPa (0.43 psig), and add the estimated air-entry pressure, yielding the minimum required operational pressures (see Section 5.2.3.3). Water table fluctuations must be considered when estimating the top of screen depth below the water table.

The selected air delivery equipment must be capable of producing pressures sufficient to depress the water table below the screen in all air sparging wells and delivering the required air flow to each well. Common air delivery sources, along with a brief explanation of mechanical and operational considerations and the interrelationship with the design variables, are provided in the following paragraphs. Additional considerations, such as explosion-proof equipment, silencers, dryers, filters, and air coolers are also discussed. As with any equipment specification, the manufacturer's performance curves should be reviewed prior to purchase. All units should be rated for continuous duty.

Reciprocating Air Compressors. These units are used when high pressure is required and a low flow rate is acceptable. Only oil-less units should be used to eliminate the potential to inject oils into the subsurface if mechanical failure occurs. These units are capable of producing substantial pressures that could cause manifold problems. Therefore, an automatic pressure relief valve on the air compressor outlet should be specified for this type of unit.

Rotary Screw Air Compressors. While possessing a wider range of capability for air sparging service, these units typically contain oil that could accidentally be discharged into the subsurface. Therefore, a filter is needed to ensure removal of any oil in the air compressor outlet. These units are acceptable for air sparging service, but may require more maintenance than reciprocating compressor units.

Regenerative Blowers. This type of blower is typically used for applications of up to 69 kPa (10 psig), i.e., sites conducive to air flow at low pressures. There are several advantages associated with using these units, including low capital cost, low maintenance, and oil-free air delivery. If higher pressures are required, a multistage blower system may be used.

Rotary Lobe Blowers. These units are generally capable of producing up to 103.5 kPa (15 psig). The units may have an oil-filled gear case, and a filter should be used for oil removal as necessary. If higher pressures are required, a multistage blower system may be used. Advantages of rotary lobe blowers include low maintenance and flexibility of operating pressure range by adjustment of belt drives to modify the blower speed.

5.3.3.3 Air Filtering

Air is usually supplied to the specified compressor or blower unit from an ambient air intake. Based on the location of the intake, it may be necessary to install an inlet filter to remove particle matter. If possible, the unit should be installed a minimum of 3 m (10 ft) away from possible contaminant sources (including soil venting systems). Non-explosion-proof equipment may be used if the unit and appurtenances are located in a safe environment.

It is the responsibility of the engineer to verify the safety of non-explosion-proof equipment and to specify use of explosion-proof equipment as necessary. Local electrical and building inspectors may require the use of explosion-proof equipment on a site-specific basis.

5.3.3.4 Heat and Noise Control

Compression of air can generate a significant amount of noise and heat. A silencer or appropriate noise controls should be considered for all applications, especially in noise-sensitive areas. Excess noise can typically be reduced to acceptable levels through the proper application of standard noise reduction materials in the equipment housing.

Additionally, as part of the system design, calculations should be made to determine anticipated system exhaust temperatures. Discharge piping must be able to withstand the compression discharge temperature and pressures. All discharge piping should be properly anchored to overcome pressure forces generated from the unit. The air injection discharge should have temperature and pressure sensors and switches that are interlocked into the electrical control panel for automatic shutdown when the pressure and/or temperature exceeds safe operating criteria. An aftercooler can be used to reduce the discharge temperature to acceptable levels prior to entry into manifold systems. Aftercoolers are designed to facilitate processing of condensate water that is generated due to temperature drops. If an aftercooler is not used, provisions must be made to remove moisture condensation caused by the compression of air in the supply unit or manifold piping. A receiver tank with a manual or automatic drain to remove condensate is suggested either between the air inlet and the air supply unit (for larger systems) or on the unit discharge manifold. A dryer can also be used to remove generated condensate.

5.4 Process Modifications

The air sparging systems as originally designed and installed are often modified to fit specific site conditions. Most importantly, the engineer must acknowledge that air movement patterns in the subsurface are not well understood. Therefore, the design must be adaptable to rapidly changing or unexpected conditions. Pilot test results will provide an expected range of air injection pressure for initial starting conditions. However, all areas of the site may not behave similarly with respect to air movement, and during the life of the remedial project, subsurface conditions will likely change. As a result, the original design must allow the operator to modify several parameters and be flexible in the application of sparging air. This built-in flexibility will provide the most effective system. System changes that may be required are discussed in this section.

5.4.1 Additional Air Sparging Wells

The cost of installing and piping an air sparging well is relatively low (less than 1% of the total project cost). Therefore, the price of a few additional air sparging wells to ensure overlap of the zone of influence from each air sparging well is minimal compared to the cost of having to operate the system for an additional period of time while all areas are remediated. Therefore, the design needs to allow for additional air sparging wells, especially if data collected during installation of the minimum amount of wells indicates more complicated anisotropic conditions or a different mass distribution pattern than originally anticipated. A pulsing approach may be used to supply air to all air sparging wells periodically rather than increasing the size of the air compressor due to the additional wells. Sparging wells that are not being used can serve as monitoring points when they are not in the pulsing rotation.

As with vapor extraction and bioventing systems, the ability to accommodate additional wells or different size compressors should be incorporated in manifolding and piping systems. However, unlike vapor extraction systems, additional air treatment capacity is not likely to be needed.

5.4.2 Well Screen Placement

Placing sparging points at different depths rather than only one depth may be appropriate to ensure effective distribution of air in the subsurface or to accommodate fluctuations in the water table. Separate wells are recommended for sparging at different depths in the same area. Nested sparging wells have been used for this purpose but problems may develop because the constant pressure, settling of well packings, and drying of bentonite or other seals between the screens may cause short circuiting between or among screened intervals in the nested well. Uneven hydration of bentonite pellets has also contributed to failure of nested sparging wells.

5.4.3 Sparging Curtains and Horizontal Air Sparging Wells

Sparging curtains are a series of vertical air injection wells located along a line and spaced to ensure that adequate aeration occurs between each well. This forms a zone of aeration comparable to a curtain so that any mobile contaminants in the groundwater moving through the curtain are exposed to a highly-aerated, highly-bioreactive zone. Any volatile contaminants are, therefore, subjected to conditions favoring rapid volatilization and biodegradation. For low-concentration, dilute plumes with known groundwater velocities, this approach may be successfully used to create a treatment zone downgradient from a migrating plume. Groundwater monitoring wells and piezometers up- and downgradient of the sparging curtain are used to ensure the hydraulic gradient is maintained through the curtain and that treatment is effective in removing contaminants. In this application, a high air flow rate, which favors more dense channel formation, is critical to success. Higher air flow rates may displace sufficient water such that soil pores are filled with air — a condition which inhibits and can even prevent groundwater movement through the sparging curtain. Because of this, sparging curtains are usually operated in a pulse mode, with the "on" cycle correlated to the rate of groundwater flow through the curtain.

Section 3.2.4.4 describes how horizontal wells are installed and used for vapor extraction. Air sparging horizontal wells are installed in the same fashion but below the water table. Special provisions for handling drilling liquids, especially if NAPL may be encountered, during installation. If the potential target for injected air and the extent or shape of the impacted area lends itself to a linear, horizontal injection system and other site conditions favor horizontal installation methods, then a horizontal air sparging well can be most effective and least costly. However, due to the relative low cost of vertical, driven well points that are typically used for air sparging, the added cost of a horizontal well may not be justified unless access for vertical wells is not possible.

The same limitations of horizontal vapor extraction in a horizontal well apply to air sparging in terms of air flow through the screened interval. To minimize the possibility of injected air being concentrated in one area of the screen, the screen slot size or openings can be varied along the length of the screen with smaller openings near the air source and larger openings at the farthest point from the air source.

An alternative and potentially more effective method is to install sections of blank pipe between small screened sections to ensure even air distribution during air sparging. Finally, for longer horizontal sparging wells (more than 15 m [50 ft]), provisions must be included for monitoring the air flow, pressure, or dissolved oxygen (within 1.5 m [5 ft] of the well) at intervals along the screened interval to ensure that the entire length of screen is delivering air evenly.

5.4.4 Heated Air Sparging

In some cases, injected air has been heated to improve VOC stripping and recovery and to enhance biodegradation. However, the heat capacity of air compared to soil and groundwater is very low. Consequently, the ability to heat groundwater with sparged air is limited and would normally take weeks to months. This approach is attempted only with stagnate groundwater such as in perched groundwater zones. Air-to-air heat exchangers or the exhaust from a catalytic oxidizer are used to heat air prior to injection. If exhaust air from a thermal oxidizer unit is used, the oxygen content may be substantially decreased, especially if the VOC loading in the feed air to the oxidizer is heavy. This can slow biodegradation effects considerably, and in such cases, an air-to-air heat exchanger is recommended to facilitate both diffusion/ transport and biodegradation benefits from air injection. When using heated air, all materials delivering such air must be capable of withstanding the maximum operating temperatures.

5.4.5 Ozone Sparging

A recent development in air sparging technology has been the use of ozone gas mixed with injected air. Ozone is a chemical oxidizer which, upon contact with VOCs, can break down chlorinated and nonchlorinated VOCs to simpler molecules that are more readily biodegraded. In addition, ozone, upon contact with organic matter, liberates oxygen which enhances biodegradation of residual organics. Another benefit of ozone is that the injected concentration is very low (less than 3% by volume) thus reducing the hazard of exposure to the injected air. There are few data available showing that ozone is more effective than air for common VOCs. Ozone may be more effective for contaminants with low volatility or high solubility, which would not generally be removed with traditional sparging. Ozone is not stable in groundwater and can quickly dissipate. Therefore, pilot testing is recommended for this approach.

5.4.6 Air and Methane Mixture

Indigenous methanatropic organisms can be biostimulated with the addition of methane as an electron donor and oxygen as an electron acceptor. Methanotrophs produce the enzyme methane monooxygenase (MMO), which initiates the first step of methane oxidation when methane is used as the sole carbon source for energy and growth (Semprini et al. 1990). Under aerobic conditions, MMO can epoxidize alkenes. Aerobic TCE oxidation can be accomplished by mixed cultures of methanotropic and heterotrophic organisms. TCE oxidation first involves the epoxidation of TCE by methanotrophs, an abiotic hydrolysis of the epoxide to nonvolatile products, followed by heterotrophic degradation of the products to CO_2, chloride, and water (Semprini et al. 1990).

Laboratory studies have shown that this process can be conducted aerobically with an air phase that contains as little as 0.6% natural gas (i.e., methane) by volume (Wilson and Wilson 1985). In microcosms, optimum gas-phase oxygen and methane content to promote TCE degradation were determined to be between levels of 7.7 to 8.7% and 1.7 to 2.7%, respectively, which correspond to aqueous concentrations of 3.2 to 3.7 mg/L and 0.4 to 0.6 mg/L, respectively (Kane, Fischer, and Wilson 1996).

A comprehensive investigation of the addition of methane to sparging air to enhance the biodegradation of TCE is planned at the USGS field research site located at the Picatinny Arsenal, New Jersey (Fischer, Wilson, and Kane 1995).

Methane can be added to sparging air by piping a methane line equipped with a check valve, isolation valves, and flow meter to a sparging well. The methane supply must produce sufficient line pressure to overcome pressure resulting from the air sparging compressor or blower. Methane content of sparging air should be maintained below the LEL of 5% to prevent explosive conditions. The methane addition must occur only when a sparging blower is operating; this can be accomplished with an interlocked valve rated for natural gas service.

Methane injection via sparging continues to be the focus of research. Currently, little is known about when and how to apply methane injection.

Consequently, methane injection is still considered a research modification of groundwater sparging.

5.4.7 Pure Oxygen

Delivery of oxygen is often the rate-limiting step controlling biodegradation. Air contains approximately 20% oxygen by volume. When using air as a sparging gas, the maximum DO concentration that may be obtained within an aquifer is 8 mg/L, based on partitioning described by Henry's Law at typical groundwater temperatures. Soils with low permeabilities may severely restrict the rate at which sparging gas, and therefore oxygen, can be introduced into an aquifer formation. When sparging gas flows are restricted to less than 2 scfm, the use of pure oxygen as a sparging gas should be considered. With 100% oxygen as a sparging gas, the resulting DO level is 40 mg/L. Therefore, the amount of DO delivered and rate of biodegradation can be as much as five times faster than air when using pure oxygen as a sparging gas. This benefit may offset the lower sparging gas flow rates. Additionally, higher DO concentrations result in greater concentration gradients and higher rates of mass transfer to areas not directly contacted by sparging gas. Furthermore, in biosparging applications, the injection of pure oxygen can provide a means of effective sparging in geologic conditions not suited to traditional air sparging.

As an example, a biosparging pilot study was conducted for groundwater and soils contaminated with semivolatile organic compounds at a facility in Texas used to store wastes and waste waters containing elevated levels of nitroaromatic and aromatic compounds. Site operations led to release of these compounds into the groundwater, which was located in a confined sandy aquifer underlying a clay aquiclude. These site conditions prevented implementation of a cost-effective vapor extraction system for sparging gas capture. The pilot study demonstrated the successful application of pure oxygen into the aquifer. At an oxygen flow rate of less than 1 scfm, a zone of influence in excess of 9.1 m (30 ft) was observed.

5.4.8 In-Well Aeration Systems

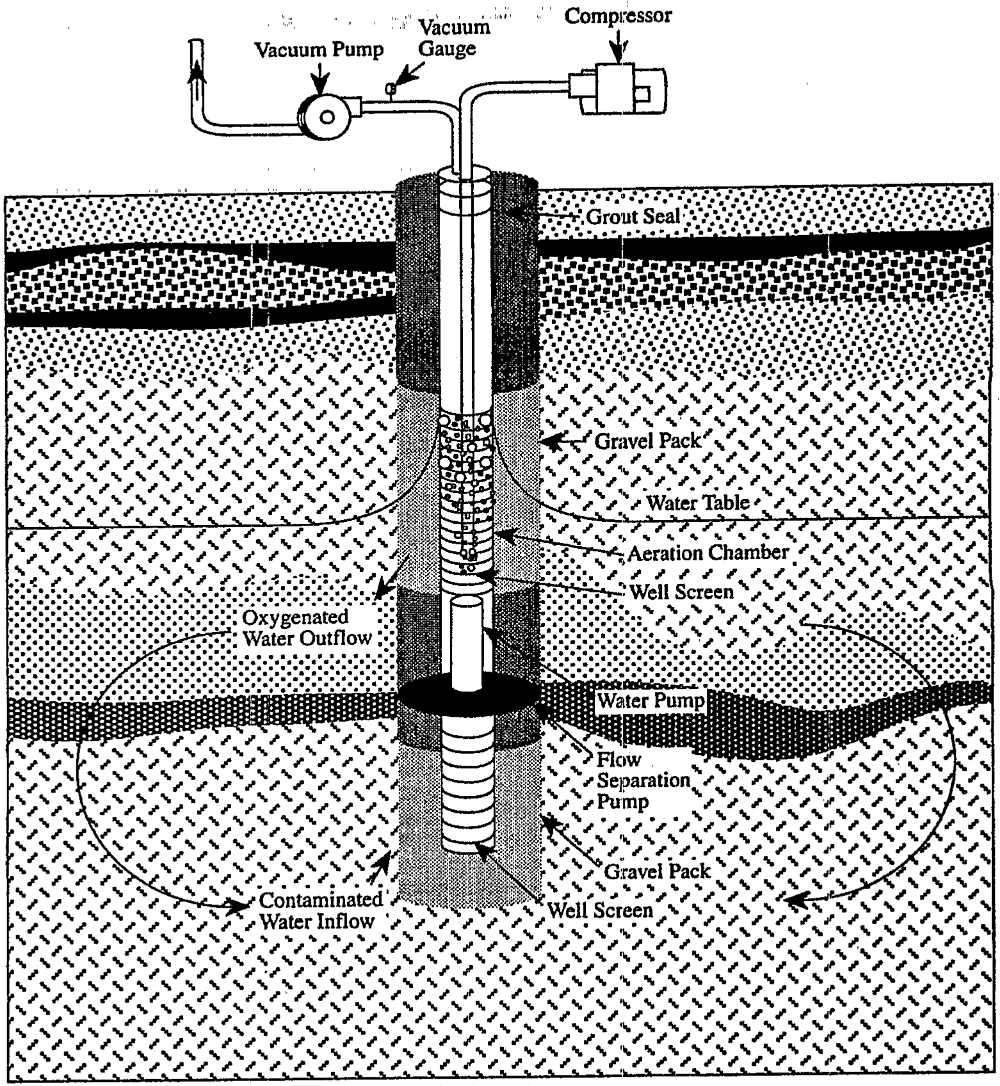
In-well aeration (also called groundwater circulation and air lifting pumping) uses specially designed multiple screened wells in which a pressure gradient is established between the isolated screen intervals. This pressure gradient results in groundwater recirculation within the aquifer in the vicinity of the well. As contaminated groundwater is brought into the well it is treated via in-well air stripping. The injection of air into the well performs two purposes: (1) it establishes a pressure gradient via air lift pumping; and (2) it air strips VOCs from groundwater within the well. The vapor phase VOCs are collected either from within the well or via a SVE well located near the recirculation well. Figures 5.5 through 5.7 depict three patented approaches to in-well aeration. The primary differences in the three approaches involve the manner in which a pressure gradient is established and the location of the upper screened interval with respect to the water table.

The recirculation well is typically installed to a point near the bottom of the groundwater plume such that the full depth of the plume is within the capture zone when air is fed through. The inner well casing is typically perforated at two depths: (1) within the saturated zone where the casing is in contact with the contaminant plume, and (2) within the vadose zone at a selected height above the water table. Air is injected by means of a compressor and interior pipe so that a continuous stream of bubbles is formed in the casing starting just above the lower perforated section. The gas may be air, oxygen, or nitrogen depending upon geochemical considerations. Air is the least expensive alternative, but may cause biofouling or oxide precipitation.

Oxygen can enhance bioremediation in the formation, but is more expensive. Nitrogen is used to prevent oxidation-related fouling. Regardless of the gas selected, its introduction constitutes an air lift pump (i.e., the presence of the bubbles in the casing causes the column of water in the casing to have a lower density than the water outside the casing and, as a result, water flows into the well in response to the pressure differential). The inflowing groundwater carries dissolved VOC contamination with it.

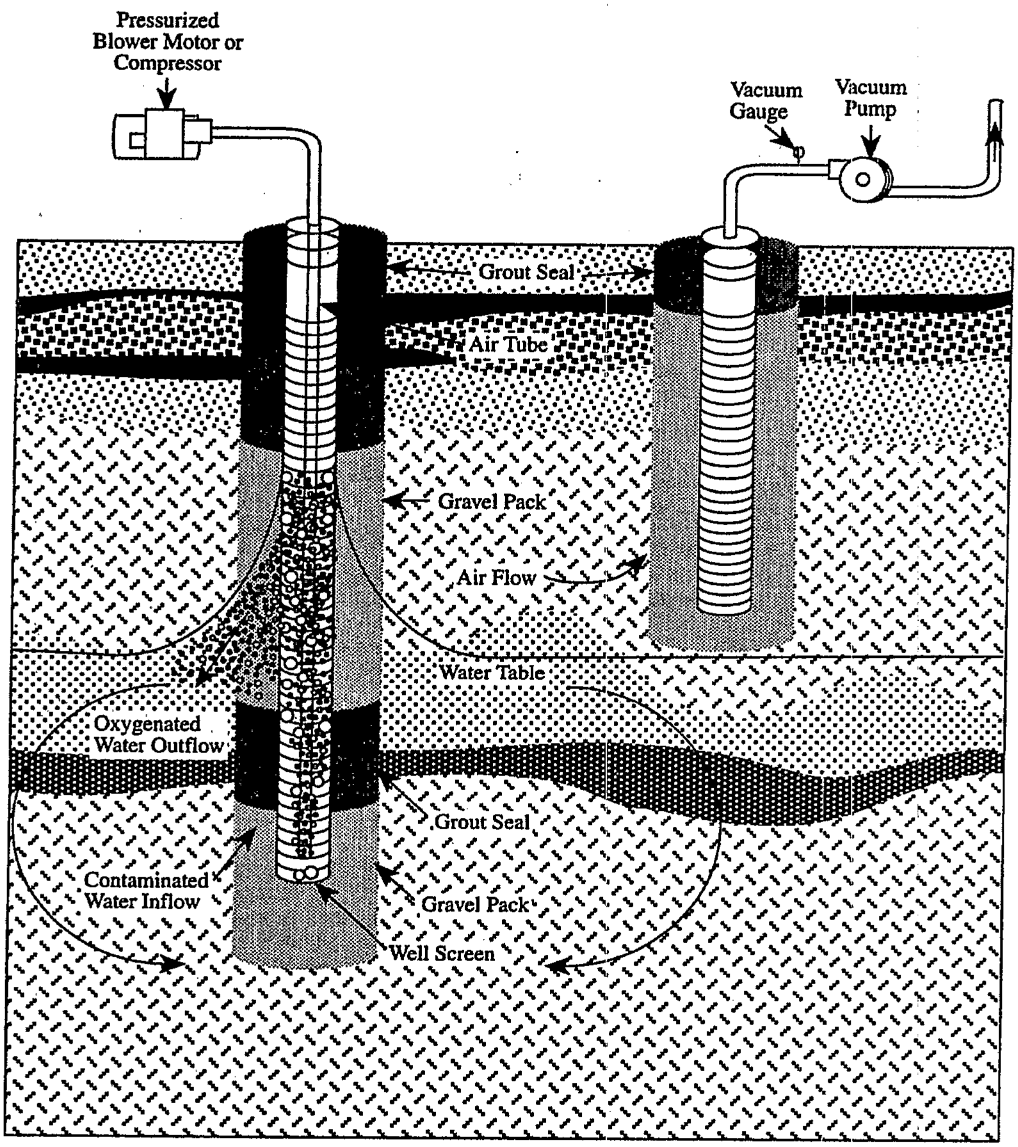
A packer or solid deflector plate is installed at the top of the casing just above the upper perforated zone. The packer prevents the combined flow of water and vapor from rising any higher in the casing, thereby forcing it to pass out through the perforations into the vadose zone. A second outer well casing of larger diameter than the inner well is positioned around the inner well from the packer to the ground surface. The annular space between the inner and outer casings is maintained under vacuum by means of a blower or ventilator whose exhaust is directed to an offgas treatment unit.

Figure 5.5
UVB System Combined with Vapor Collection



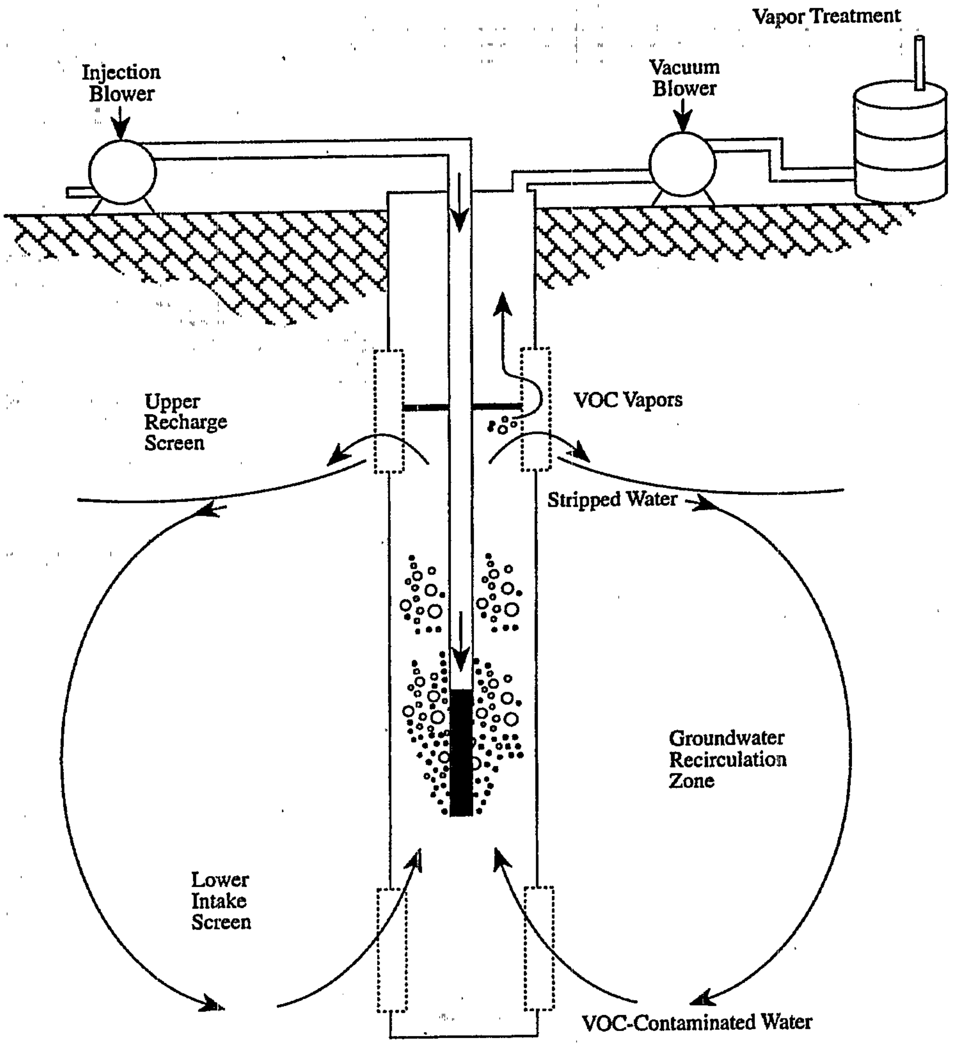
Reproduced courtesy of SBP Technologies, Inc.

Figure 5.6
Density-Driven Convection System with Vapor Extraction



Reproduced courtesy of Wasatch Environmental, Inc. (U.S. Patent Number 5,425,598)

Figure 5.7
A NoVOCs™ System



Reproduced courtesy of MACTEC, Inc.

When operated, the air lift pump draws contaminated water into the inner well where volatile contaminants vaporize as they are transferred into the bubbles in the water column. The transfer continues until equilibrium is reached as defined by Henry's Law. At the packer, the bubbles break and coalesce. The water percolates downward through the vadose zone, while the contaminant vapors are drawn off by the vacuum in the outer well. Since the Henry's Law constant for most contaminants is insufficient to produce drinking water quality on a single pass, the pumping rates and well placement are selected to accommodate multiple cycles for each unit of water. The optimum number of cycles is dependent on the starting concentration and the flow rate of the ground water. Some additional removal occurs in the vadose zone where the soil particles act like packing in an air stripper. The degree of additional removal achieved will depend on the size of the soil particles, the amount of flow induced by the vacuum, and the degree of saturation produced by the infiltrating water.

Even though in situ air stripping is commonly discussed in conjunction with groundwater sparging, it is really more similar to a groundwater extraction treatment method, subject to many of the same limitations of groundwater pump-and-treat technology. There is no sparging of air through saturated zone soil.

5.4.9 Nitrogen Sparging

Nitrogen has been used on only a few occasions, and these were usually at sites where high iron concentrations occurred in the groundwater. Nitrogen was used in an effort to prevent oxidation of the iron and potential clogging of the aquifer. The most economical way to generate nitrogen on-site is with use of a pressure-swing adsorption unit. These units use adsorption resins to separate nitrogen from oxygen in atmospheric air. While skid-mounted units are available, energy requirements are substantial. For example, a pressure-swing adsorption unit that can produce a 40 scfm flow of nitrogen may require a 60 to 70 hp motor. The energy cost of these units along with the inconclusive data regarding iron clogging have resulted in infrequent use of nitrogen sparging.

5.5 Pretreatment Processes for Air Injection Systems

Little pretreatment is required for injection of air into the groundwater. Some treatment of the compressed air may be required to (1) reduce the temperature and/or (2) to reduce the oil and water. At other times, injecting a gas other than air may be required for a site.

5.5.1 Temperature Reduction

Positive displacement blowers are often employed when sparging pressures are less than 103.5 kPa (15 psi). The temperature increase resulting from air compression may be significant. Temperature increases for a given blower can be obtained from the blower manufacturer's literature. Many types of flow meters, as well as PVC piping, are designed for temperatures less than 60°C (146°F). Compressing ambient air to 69 kPa (10 psi) can increase the blower exhaust air temperatures to exceed material temperature ratings for some piping and meters.

Consequently, some sparging designs need to include heat exchangers. In some cases, the required heat exchange can be conducted through passive techniques, such as running extra steel piping on the roof or below the blower building. This allows the piping to dissipate the heat in the compressed air to acceptable temperatures. The success of such passive systems may depend on the climate and amount of heat reduction required. Passive techniques are particularly effective in northern climates.

A more robust heat reduction system includes the use of an air-to-air heat exchanger. In these heat exchangers, a fan blows ambient air across metal pipes carrying the compressed gas, and in the process, cools the compressed gas to within a few degrees of ambient temperature. Heat exchangers can be controlled so they come on and off with the blower. They are relatively low cost and provide protection of other equipment as well.

5.5.2 Oil and Water Removal

For larger sparging systems requiring more than 103.5 kPa (15 psi) for injection, rotary-screw compressors are often used. Such compressors are normally fitted with receivers to hold the compressed air. Since air from these compressors is not oil free, oil filters (centrifugal and/or coalescing) need to be fitted on the discharge from the compressor. An oil filter can remove more than 99.99% of the oil carried over from the compressor. Water can also condense in the receiving tank; thus, these tanks need to be equipped with a discharge line to remove water.

5.6 Posttreatment Processes

For groundwater sparging, posttreatment processes are those which treat contaminants volatilized into the vadose zone. Volatilized contaminants need to be treated further through either natural biodegradation in the vadose zone or active collection with a soil vapor collection system. These concepts are discussed further in Section 3.5.1.

5.7 Process Instrumentation and Controls

Refer to Section 3.6 for a discussion of instrumentation and controls applicable to vapor extraction and bioventing, much of which is also applicable to air sparging systems. This section highlights aspects of instrumentation and controls that are unique to an air sparging system.

5.7.1 Air Sparging Instrumentation and Controls

Due to the presence of pressurized air, several sensors, relief valves, and controls are necessary to ensure a safe and functional system. The following sensors, switches, and controls are recommended for all air sparging systems:

- pressure gauges at each wellhead, manifold, and compressor air storage tank;
- pressure relief valves at the compressor and for the sparging air piping system — all set to release pressure at an adjustable set point, but no greater than the maximum design pressure;
- pressure regulator between the compressed air source (air compressor) and the air sparging well field;

- temperature sensor and switch on the outlet side of the air compressor to protect the piping;
- electrical interlock to allow air sparging operation only in conjunction with concurrent vapor extraction;
- control valves on each line to each sparging well and at each wellhead;
- check valves at each sparging well to prevent the backflow of air toward the blower when it is shut down;
- Pressure/vacuum and flow indicators for each well, of the appropriate range for anticipated conditions;
- Air compressor motor thermal overload protection;
- Pressure relief valve or vacuum switch to effect blower shutdown; and
- Explosimeter within enclosed spaces at sites with recently measured LEL levels greater than 10%.

5.7.2 Instrumentation Selection

As with vapor extraction and bioventing systems, all materials used for delivering air to the subsurface (well materials, diffusers, etc.) must be compatible with the concentration of contaminants present. Although the instruments installed will contact moisture-laden air and possibly water in injection lines due to condensation, the compressed air system and delivery piping will not normally come in contact with the contaminants. Therefore, function, serviceability, and cost factors will drive the selection of instruments in the equipment building.

Instruments located in well vaults and air injection lines will be subject to high humidity and wet conditions and must be corrosion resistant. Air flow sensors and differential pressure sensors must be able to function in high humidity conditions (inside the piping) and withstand weather extremes outside in well vaults or unheated spaces.

5.7.3 Controls and Alarms

The primary control elements in an air sparging system are the pressure and temperature of the injected air. Overpressuring can lead to low channel density due to soil fracturing. Most air compressors are sold with internal pressure-regulating devices that allow the delivery of air within a specified pressure range. Typically, this range is much higher than the pressure necessary for air sparging, and therefore, a pressure regulator is required downstream of the compressor.

A pressure relief valve is also mandatory on the piping side of the compressor to prohibit pressures above the design maximum from developing in the air sparging piping network. Each air sparging well must have a flow control valve that allows the operator to adjust the air flow throughout the anticipated design range at each wellhead. Air flow monitoring ports are needed at each wellhead or at each manifold to ensure air flow is occurring in all wells.

5.7.4 Remote System Monitoring/Telemetry

An introduction to remote monitoring and telemetry devices is presented in Section 3.6.4. For air sparging systems, remote monitoring parameters to be tracked by will include sparging manifold pressure, compressor motor operation, and vapor extraction blower function. These parameters will verify that the system is operating within the design range and that the vapor extraction system is operating if the air sparging system is operating. More advanced telemetry units, when combined with on-line instrumentation for air flow and VOC concentration, can track and transmit mass removal information continually. Such controls are installed only in more complex and long-term operating systems.

5.8 *Safety Requirements*

Section 3.7 discusses safety requirements that are also applicable to air sparging. This section highlights the special safety requirements of an air sparging system.

Air sparging typically generates higher air pressures than bioventing. In both cases, compressed air can create a serious hazard. To provide for safety, pressure relief valves are mandatory on all air sparging piping and wells as previously discussed.

Air compressors have their own set of safety precautions. Any moving parts such as flywheels or belts must be enclosed to prevent entanglement of clothing or limbs. When compressor air storage tanks are emptied periodically to remove accumulated condensate, the rush of compressed air from the drain valve can project liquid and air a significant distance; gradual bleed ing of the accumulated pressure and eye protection are two recommended precautions.

5.8.1 Building Code

The same recommendations for building code compliance for vapor extraction and bioventing, presented in Section 3.7.2, apply to air sparging.

5.8.2 Electrical Code

The same recommendations for electrical code compliance for vapor extraction and bioventing, presented in Section 3.7.3, apply to air sparging.

5.8.3 Designing for Operational Safety

Several design factors that contribute to the safety of a vapor extraction or bioventing system are presented in Section 3.7 and are directly applicable to air sparging systems. One notable addition to these safety considerations is that air sparging is commonly conducted concurrent with vapor extraction. Therefore, electrical interlocks are required to allow the operation of the air sparging air compressor or the air sparging piping control valve only when the vapor extraction blower is activated. In addition, flammable gas detectors or explosimeters should be placed in enclosed buildings within VOC impacted areas where air sparging will be performed. These detectors should be interlocked to shutdown the air sparge system when they detect explosive or hazardous conditions.

5.9 Drawing and Specification Development

A discussion of drawings and specifications for vapor extraction and bioventing systems is presented in Section 3.8. This section focuses on additional drawings or specifications that are necessary for an air sparging system.

Additional Drawings:

1. *Site Plan.* The site plan and layout must show air sparging wells and piping locations. As with vapor extraction and bioventing systems, a schedule of wells to be used for air sparging and monitoring air sparging effectiveness provides an efficient way to identify which wells are existing, those that will be converted to sparging or monitoring use, and those that will be drilled; the well screen intervals; etc.
2. *Well and Piping Construction Details.* Cross sections of each different sparging well are needed to illustrate depth of screen placement, construction materials, wellhead details, valves, monitoring access points, etc.
3. *Process and Instrumentation Diagram.* A separate P&I diagram for the air sparging system is recommended. This diagram must show the pressure regulation, pressure relief, and control valves necessary for a safe air sparging system. Electrical interlocks to the vapor extraction or bioventing system must also be shown.
4. *Mechanical Details.* The mechanical drawing(s) should illustrate details of sparging pipe manifolds, attachment of pressure and air flow measurement devices, etc.
5. *Electrical Plans.* In addition to the items listed in Section 3.8, the electrical plan must show the air compressor, power source, power for instrumentation, interlocks or logic for concurrent vapor extraction and air sparging operation, etc.
6. *Building or Equipment Enclosure.* This drawing must show the air compressor or the source of compressed air, manifolds for the sparging system, etc.

5.9.1 Wells/Trenching/Field Piping

Well packing must be compatible with the geologic formation to prevent short circuiting to the surface. Section 3.8.3 provides detailed information on wells, piping, valves, etc. that is directly applicable to air sparging.

5.9.2 Equipment

Equipment, in addition to that described in Section 3.8.4, includes the sparging air compressor. At a minimum, compressor specifications include the volumetric flow rate of air under various pressure conditions, pressure range, temperature rise at compressor discharge point, recommended lubrication requirements, oil type, electrical requirements, motor starter, and thermal overload for motor (may or may not be included in vendor package).

5.9.3 Electrical

Electrical specifications must include the power requirements of the air compressor and related control and instrumentation.

5.9.4 Mechanical

Mechanical specifications for an air sparging system will include the operating range of the air compressor, pressure relief valve specifications, piping specifications, wellhead detail, check valves (at each wellhead), and sampling points.

5.10 Cost Estimating

Refer to Section 3.9 for a breakdown of costs applicable to vapor extraction and bioventing systems. In addition, the costs of the air sparging compressor, air drying unit (if needed), piping (to the extent that vapor extraction trenching cannot be used), instrumentation and controls for the air sparging system, well vaults, well drilling, etc. must be considered.

5.11 Design Validation

Design validation refers to the ongoing process of checks and improvements carried out in the design planning, construction, startup, and operational phases. Since interpolation and extrapolation of subsurface site conditions from a small percentage of the soil actually observed and tested during a typical site investigation is necessary, there is inherent uncertainty associated with any subsurface design. The uncertainty for sparging design is compounded since small changes in soil permeability can dramatically affect system performance. While uncertainty cannot be overcome, provision for contingencies can be incorporated into the design and implementation process.

During the conceptual design phase, the engineer must identify what may go wrong and how site conditions may vary from assumed. During the preliminary design phase, strategies for assessing changing geologic or contaminant distribution conditions must be developed. These strategies may include layout of the monitoring system (piezometers, monitoring wells, offgas monitoring points) and system flexibility (additional smaller blowers instead of fewer larger ones, expandable manifolds, easily changeable offgas treatment options, burying extra pipes in trenches, etc.). Decision trees should be developed during the preliminary design phase to show how system layout or operating parameters can be varied for changing site conditions or if cleanup criteria are not met at compliance points.

During construction, further site knowledge is typically gained through the installation of additional wells or excavations. Processes need to be in place so that (1) additional site information is collected during construction by the field staff and (2) this knowledge is conveyed to the engineer so that field changes can be made as needed. For instance, the depth of contamination may be deeper than first estimated and therefore, the depth of the sparging wells must be modified. Finally, during system operation, the monitoring plans need to be implemented based on observed operating data with changes in layout or operation as appropriate.

5.12 Permitting Requirements

Air and water discharge permitting requirements are covered in Section 3.11. Generally, states do not require a specific permit to conduct an air sparging test beyond the requirements for air and water discharge permits.

Depending on the regulatory program and degree of state involvement, various levels of monitoring requirements may be implemented. Some states may also have design guidance regarding the amount of air injected in a sparging system versus the amount of air removed with an vapor extraction system, monitoring programs, and minimum provisions for pilot- and full-scale operational reports. However, these should be considered requirements to assess and document the overall performance of the pilot test or full-scale system, rather than compliance requirements.

Also, there may be related provisions regarding well construction or abandonment, well identification, investigative waste disposal, and electrical safety that must be followed. For an example of more detailed state guidance for sparging systems, refer to the Wisconsin Department of Natural Resources' *Guidance for Design, Installation, and Operation of In Situ Air Sparging Systems* (1993).

When a gas other than air is being sparged, states typically require a groundwater injection permit. In such cases, the gas to be used, its intended effect on contaminants in the groundwater, and how uncontrolled migration of the injected gas will be monitored must be documented.

5.13 Design Checklist

This section summarizes the activities to be considered during design of an air sparging system in checklist form. While not all items may be needed for a particular project, the checklist provides an overall list of concerns/activities that should be considered.

Site Investigation/Regulatory Review

- Develop target zones from site investigation report
- Construct cross-sections from soil borings showing target cleanup zones
- Develop list of potential environmental permits
- Develop preliminary soil and groundwater clean-up concentrations
- Determine list of chemicals of concern

Design Planning

- Develop overall design objectives, including desired timeframe for remediation
- Complete conceptual design of treatment system for the site including cross-sections and plan views
- Estimate contaminant mass to be removed/contained
- Identify need for pilot test based on size and complexity of site
- Identify data objectives of pilot test
- Assess need for pilot test and full-scale offgas treatment
- Identify other factors that will affect design such as space, proximity to electrical power source, noise, facility operations, property, and access constraints
- Determine how the system will be built and relationship between designer/contractor/operator

Preliminary Design

- Complete pilot test work plan
- Undertake pilot test
- Interpret pilot test results in terms of initial conceptual design; modify conceptual approach as required
- Layout aboveground aspects of system, including piping runs, equipment locations, discharge points
- Estimate total flow and mass removal rate; determine need for soil vapor extraction

- Begin application for air and water discharge permits
- Develop a list of major equipment items and their preliminary sizing
- Complete a piping and instrumentation diagram showing controls and interconnects
- Consider future modifications that may be required for the system
- Determine how discharge compliance and eventual soil cleanup will be demonstrated
- Determine electrical classifications
- Determine how subsurface air flow will be assessed during full-scale operations

Final Design Activities

- Complete analysis of system pressure requirements with head loss assumptions
- Finalize blower sizing as well as other major equipment
- Complete civil construction details and specifications (well, trench, building foundation details)
- Complete final mechanical drawings and specifications of piping and equipment
- Complete final electrical and instrumentation and control drawings and specifications
- Complete final architectural drawings for buildings as needed
- Develop construction quality assurance plan, including functional and performance checking of the system
- Develop a start-up plan, including samples to be collected and analyzed
- Develop an operations and maintenance plan for long-term system operation; include contingency plan for system modifications as required, reporting requirements, safety, compliance
- Develop a construction and operation safety plan
- Develop a final cost estimate for construction and operation

6

IMPLEMENTATION AND OPERATION OF AIR SPARGING

6.1 Implementation

Implementation of an air sparging system follows essentially the same procedures as those described for a vapor extraction system as described in Section 4.1.

6.2 System Startup

While carefully following a detailed start-up plan is important with any system involving multiple motors, blowers, pumps, and piping systems, it is especially important for air sparging systems. This is primarily because air sparging systems present potential hazards above and beyond those of other systems. These supplementary hazards include:

- conveyance of compressed air that, if suddenly released, could present a health and safety hazard; and
- the generation of hazardous vapors in the subsurface that could migrate to sensitive receptors.

This section discusses prudent activities that can be taken to minimize the hazards associated with startup of air sparging systems. A general start-up checklist is also provided.

6.2.1 Component Testing

As discussed in Section 4.2.1, component and system diagnostic testing may be the most important of the start-up tasks. Such testing:

- ensures that equipment has been installed to operate in accordance with manufacturer's specifications;
- verifies that the system has been installed to operate safely; and
- confirms that the automated safety control logic was programmed into the system in accordance with the design.

Specific component diagnostic testing that should be included in system start-up activities include rotating of equipment, electrical safety checks, and testing of automated shutdown protocols.

6.2.1.1 Power Supply

The direction of rotation of pumps, blowers, compressors, and other equipment is often established by the electrician when connecting the unit to the power supply. Because an incorrect direction of rotation can adversely affect the performance and possibly damage the equipment, the rotational direction of rotating equipment needs to be checked prior to continuous operation. A general discussion of the necessity for, and methods of, verifying the proper rotation of remediation equipment is provided in Section 4.2.1.1. The guidance in that section also applies to air sparging systems.

6.2.1.2 Electrical Safety Checks

Electrical safety precautions and inspections prior to air sparging system startup are comparable to those applicable to vapor extraction system operation. These recommended safety measures are discussed in Section 4.2.1.2.

6.2.1.3 Shutdown Protocols

Air sparging systems, like vapor extraction systems, are typically designed to be fully automated, requiring only periodic operator involvement. With this degree of automation, calibration of control instrumentation and testing of automated system shutdown protocols during system startup is essential to ensure that equipment is adequately protected and that system operation will not present a health and safety hazard. The calibration and shutdown simulation procedures described in Section 4.2.2 for vapor extraction systems are directly applicable to air sparging systems. However, typical shutdown protocols that are specific to air sparging systems warrant further discussion here.

One of the chief operating concerns for air sparging systems is the production of hazardous vapors in the subsurface and the possibility that these hazardous vapors could escape the confines of the system and enter and accumulate in one or more locations where sensitive receptors may be present (e.g., residential basements, utilities, buildings, etc.). The accumulation of vapors may present not only an exposure hazard to inhabitants or workers, but also, in the worst case, an explosion hazard. To minimize these potential hazards, air sparging systems typically have instrumentation and control devices that are designed to detect possible loss of subsurface vapor flow control and to terminate the sparging component of the system if this event arises.

A frequently employed instrumentation/control logic to alleviate the concerns surrounding fugitive vapors ties the supply of sparging air to the sparging wells with a measure of adequate vacuum applied to surrounding vapor extraction wells. In this safety system's simplest form, a pressure switch that is mounted on the vapor extraction system manifold piping de-energizes a solenoid valve on the air sparging compressed air manifold to cut off sparging air flow in the event that an insufficient vacuum is detected at the vapor extraction system manifold. A more complex safety net may link the supply of compressed air to the sparging wells to soil pressures detected at strategic influence monitoring wells.

Where there is an even greater threat of hazardous vapors entering and accumulating in structures, added safety measures are typically taken with respect to instrumentation and controls. One of the methods that is employed is the installation of vapor monitoring probes within likely accumulation areas of the structures. The control logic is typically programmed such that if the vapor monitoring probe(s) detect any hazardous vapor concentration above background, the compressed air supply to the sparging wells is terminated.

Should these instruments and controls be included in a system design, they represent the most important and critical part of the system. As such, particular care must be taken at startup to calibrate the instruments, verify the alarm set points, and simulate the alarm condition to confirm that the design shutdown sequence occurs. Subsequent to the start-up phase, these procedures should be repeated on a regular basis to ensure operation of these critical functions.

6.2.2 Leak Testing

Leak testing of air sparging system piping during startup is typically performed for the following reasons:

- an undiscovered leak can lead to reduced system performance and effectiveness (e.g., if the air compressor cannot supply a sufficient volume of air to the sparging wells due to excessive air loss);
- a detected leak may be indicative of a larger installation problem that if uncorrected could lead to a catastrophic pipe failure; and
- a subsurface air leak could result in a localized pressure build-up in the soil that could deflect hazardous vapors away from vapor recovery wells.

Pipe leak testing is typically completed using either hydrostatic or pneumatic testing methods. A basic description of both testing methods is provided in Section 4.1.4.3.

6.2.3 System Shakedown

An important step in the startup of an air sparging project is a full-system shakedown. Each mechanical and electrical component of the system is checked for functionality over an operating range that spans the design operating conditions. The system is operated in both manual and automated modes under a range of operating scenarios. In the automatic mode, the alarm conditions that precipitate automated equipment shutdown are once again simulated to verify final set points and shutdown protocols.

During the system shakedown, pressure and vacuum relief valves are tested to ensure that the valves are set to open at the appropriate pressure/vacuum. The air sparging system is typically ready for continuous operation once the system shakedown has been successfully completed.

6.2.4 Pre-Startup Checklist

The following checklist is typical for the pre-startup phase of air sparging implementation.

- Remove debris from piping interior (PVC shavings, soil, etc.)
- Complete pipe integrity testing
- Eliminate piping blockages
- Appropriately position all system valves
- Orient valving on blower piping in start-up configuration for least flow resistance
- Cross check that motor supply voltages match motor plate voltages
- Cross check thermal magnetic circuit breaker ratings with motor amperage specifications
- Verify that motors and hand switches are properly grounded
- Collect background data (e.g., static soil pressure, VOC concentrations, depth to water, etc.)
- Secure and post requisite discharge permits
- Check equipment lubricating fluid levels, if applicable
- Verify proper rotation of motors
- Record initial running amperage of motors
- Recalibrate all in-line instruments
- Check switch set-points
- Compare and adjust sensor transmitter spans relative to actual conditions
- Simulate alarm conditions and verify automatic operations
- Confirm remote access to telemetric data
- Reconfigure valving to achieve design vacuum/flow
- Compare blower/pump performance to manufacturer's performance curves
- Check vacuum at wellheads to confirm minimal piping head loss

- Record influence vacuums at influence monitoring wells
- Collect influent and effluent vapor samples for baseline field and laboratory analysis

6.2.5 Startup Checklist

Typical procedures for the startup of an air sparging system are as follows.

1. With the vapor extraction blower operating, activate the compressed air source, and using a pressure regulator, gradually increase the supply pressure until the design air flow rate for the chosen well group or the entire system is attained. (Set measure vapor extraction system emissions to verify compliance with permit conditions.).
2. Balance the air flow to each air sparge well.
3. Establish the applied pressure and compressed air flow relationship for each well.
4. Following flow balancing, check for agreement between flow meters to verify that total air supply equates to the sum of the supply to the individual wells.
5. Periodically collect water level measurements, soil pressure/vacuum measurements, and soil gas VOC concentrations.
6. Adjust system pressures/flows if unsafe conditions are observed from the vadose zone monitoring data.
7. Repeat for each of the air sparging well groups.

6.3 Operation and Maintenance

The success of a remediation project can depend heavily on the manner in which the system is operated and maintained. Carefully operated systems generally result in a reduced clean-up time while minimizing safety hazards. Well-maintained remediation systems tend to operate with an increased level of efficiency and with less downtime. This section discusses a number of key operation and maintenance procedures for air sparging systems that can optimize performance.

For most air sparging systems, the primary objectives of a system operation and maintenance program are to:

- achieve the remedial objectives at the earliest date;
- prevent further environmental impact via waste streams or contaminant mobilization;
- maximize the lifetime of the equipment;
- collect sufficient data to help realize these objectives;
- achieve project objectives while keeping present-value project costs to a minimum; and
- ensure safety of operation.

Controls that can be employed to optimize system operations and help achieve these objectives are discussed in subsequent sections.

6.3.1 Performance Control Functions

To optimize system performance, the operation of air sparging systems may be controlled in three basic ways. System adjustments may be made to modify:

- magnitude of applied vacuums to the soil and air sparging pressures (extracted/injected air flow rates);
- configuration of wells to which the vacuums/pressures (extracted soil gas/injected sparging air flow) are applied; and
- duration of applied vacuums/sparging pressures (extracted/injected sparging air flow).

Performance optimization is achieved when these adjustable parameters are regularly reconfigured to achieve the system's performance objectives at the least present-value cost. For air sparging systems, optimized performance typically means that VOC mass recovery rates are maximized over the period of system operation, while ensuring that the system is operated safely. For biosparging systems, this typically means the uniform and consistent delivery of oxygen to the entire treatment area to safely maximize the biodegradation of organic contaminants.

Routine collection and evaluation of system operating data provides the information that is needed to make the regular system adjustments to optimize performance. By adjusting these three basic control functions, subsurface air flow patterns may be modified to direct air toward (1) pockets of dissolved- and adsorbed-phase VOC contamination, (2) areas where oxygen levels are depressed, or (3) center of the treatment area to reduce the potential of fugitive vapors in the subsurface. These routine adjustments can also be made to eliminate no-flow zones where competition for air results in relatively static (flat pressure gradient) conditions that, if not addressed, can undermine the performance of the remediation system.

Routine system optimization adjustments are made while an air sparging system operates in either the continuous or pulsed modes. Selection of the appropriate operational mode for a given site can further optimize the performance of an air sparging system.

An air sparging system designed for continuous operation will include sparging, vapor extraction, and treatment equipment that are sized to accommodate flow to and from all wells in the system. Such systems allow for subsurface air flow to be adjusted to optimize system performance. This flexibility is important because VOC recovery rates and distribution of dissolved oxygen rapidly decrease shortly after commencing operation under a single configuration/flow regime.

One method that can be employed to reduce the degree to which channelization occurs and/or to induce air flow channel to cycle or change course during continuous operation is to routinely modify applied sparging pressure/air flows and applied vacuums. Careful evaluation of system monitoring data can reveal how the system configuration should be modified to enhance performance and the interval of time that the system should be permitted to operate prior to reconfiguration.

Air sparging systems designed to operate in a pulsed mode may have air injection and extraction/treatment capacities sufficient to employ only a fraction of the remediation system wells at one time. In such a configuration, subsets of the wells are alternately operated to optimize system performance. Where an air sparging system has been designed to accommodate the simultaneous use of all remediation system wells, pulsed operation may consist of alternately activating and terminating operation of the entire system.

The duration of a pulsing event to optimize system performance can vary. Temporary groundwater mounding during sparging may suggest what the optimum pulsing period should be for a given site. During the initial introduction of air into the saturated zone, the air displaces some of the water, creating a temporary groundwater mound. However, once stable air flow patterns in the saturated zone have developed or channelization of the air flow has occurred, the mound typically collapses as the initially dewatered zone resaturates. It has been suggested that if the duration of the transient mounding period can be determined, this period may provide a design duration and pulsing frequency for maximized groundwater mixing (US ACE 1997). However, pulsing frequency and duration should ultimately be determined based on monitoring data. Specifically, the pulse that results in the highest mass removal rate (as measured by vapor extraction mass removal rates during sparging or by declines in contaminant concentrations at compliance points) should be used.

6.3.2 Maintenance

The maintenance requirements of an air sparging system are slightly increased relative to those required to operate a vapor extraction system as discussed in Section 4.3. The increased maintenance requirements stem mainly from the addition of an air compressor and its peripherals (e.g., receiving tank, filters, dryers, etc.), the associated instrumentation and controls, and the addition of air sparging wells screened in the saturated zone. The effect of these additions on maintenance requirements is discussed below.

6.3.2.1 Rotating Equipment

Equipment rotation as described in Section 4.3.2 for vapor extraction maintenance is equally valid for air sparging systems and the reader is directed to that section for further information on the subject.

6.3.2.2 Wells, Trenches, and Well Points

The maintenance requirements for wells, trenches, and well points that were identified in Section 4.3.2 are equally valid for the operation and maintenance of air sparging systems. In addition, air sparging well screens may periodically need to be cleaned to remove accumulated fines carried into the well by water entering between pulses. Air lift pumping can remove accumulated solids within the well.

Sparge well screens may also be impacted by inorganic precipitation (primarily iron) and/or biofouling. This potential is not clearly established, and could be a function of the redox potential of the injectant, the aquifer alkalinity, the frequency of pulsing, and the type and abundance of organic complexing compounds.

A number of different methods for cleaning air sparging wells may be employed If chemical or biological fouling is present, physical agitation, or chemical treatment can be effective. In extreme cases, mineral deposits on well screens can be removed using low-pH solutions such as hydrochloric or sulfuric acid. Iron bacteria can be removed by introducing bactericides (e.g., chlorine dioxide) followed by low-pH treatment after the chlorine is removed from the well. Recommended procedures for chlorine control of iron bacteria are detailed in Driscoll (1975).

6.3.3 Safety Considerations

Air sparging systems present operator and public safety concerns beyond those discussed in Section 4.3.6 for vapor extraction systems. These additional hazards arise from the use of compressed air for air sparging and the inherent potential for air sparging to generate fugitive hazardous vapors in the subsurface.

6.3.3.1 Fire Safety

Fire safety considerations during operation and maintenance of air sparging systems are similar to those associated with vapor extraction system operation. These considerations are discussed in Section 4.3.6.1.

6.3.3.2 Air Quality

Air quality concerns during operation and maintenance of an air sparging system overlap greatly with those identified in Section 4.3.6.2 for vapor extraction systems. However, an additional air quality concern that is specific to air sparging operation warrants further discussion.

The sparging of air into contaminated groundwater generates hazardous vapors in the subsurface. During sparging, these vapors could elude capture and enter into nearby structures. If potential receptors are in the vicinity of air sparging activities, vapor monitoring within associated structures should be considered as part of the routine operation and maintenance procedures to reduce the risk of exposure to the hazardous constituents.

6.3.3.3 Physical Hazards

The physical hazards that exist with the operation of an air sparging system are similar to those discussed in Section 4.3.6.3 for operation of vapor extraction systems. However, the compressed air used in an air sparging system adds a significant physical hazard which the operator should be aware. The hazard is related to the energy that can be released during the sudden decompression of air. A sudden release of pressure due to broken piping or the decoupling of a compressed air hose can cause serious and permanent injury. Maintenance of piping protectors and safety pins in compressed air hosing connections should be mandatory, and the operator should be aware of the potential hazards of compressed air.

6.4 Performance Monitoring

The main goals of a performance monitoring program for an air sparging system should include:

- tracking the progress of remediation toward remedial goals;
- achieving the required level of remediation as quickly as possible;
- preventing further environmental impacts from waste streams or contaminant mobilization;
- collecting defensible data to support site closure;
- minimizing the costs needed to achieve the above considerations; and
- safety monitoring.

6.4.1 Zone of Influence Monitoring

The zone of influence that has been assumed during full-scale design should be confirmed once operations begin to identify any injection wells that may have zones of influence significantly different from design values.

Zones of influence should be monitored using a combination of those methods described in Section 5.2.2. If a particular well is shown to have a small zone of influence due to the screen interval being completed within a lower permeability soil zone, the applied pressure can be increased. In addition, pulsed operation in the vicinity of this "dead zone" will increase mass removal from the area.

In some cases, zone of influence monitoring data will indicate that the system is operating as designed, but contaminant concentrations at compliance monitoring points exceed acceptable levels. Although not indicated by the employed zone of influence monitoring methods, this may be due to uneven aeration of the contaminated portion of the aquifer. In these cases, the system modifications discussed in Sections 6.3.1 and 6.5 should be considered.

6.4.2 Injection Pressures and Flows

The injection flows at individual wells should be regularly monitored, and necessary valve adjustments should be made to ensure that the system flow is balanced as designed. As operational data are collected for a given system, it is common for different injection flows to be used at various wells due to water table fluctuations or heterogeneities in the aquifer or targeting of "hot spots."

A major concern with air sparging system operation is well screen and/or aquifer fouling by precipitate buildup or microbial growth. Fouling of the well or aquifer may be indicated by a reduction in injection flow rate at a given pressure over time. Therefore, it is important to regularly monitor the injection flows and pressures at individual injection wells to determine the week-to-week variability in these parameters and to identify any evidence that a loss of permeability may be occurring due to fouling and/or scaling.

6.4.3 Downgradient Groundwater Quality Monitoring

Downgradient groundwater quality is usually used as the ultimate performance monitoring measure of an air sparging system. For this reason, the groundwater quality in both up- and downgradient wells should be documented at regular intervals during system operation. These records are necessary to define:

- characteristics of contaminant source material;
- water flow velocity or direction on a seasonal basis; and
- operational changes.

Care should be taken to ensure that uniform and acceptable methods of sample collection and analysis are used during the entire monitoring period and at all wells. In this way, time trend analysis of the data can be performed without having to consider changes in sampling and/or analytical methods.

6.4.4 Vadose Zone Monitoring

As previously discussed, the vadose zone surrounding an air sparging system needs to be monitored for pressure to ensure that the injected air is collected by the vapor extraction system, if one is used. If a vapor extraction system is not used due to reliance on the vadose zone soils to act as a biofilter to the contaminants in vapors released from the aquifer, then additional vadose zone monitoring is needed.

To define the extent to which contaminants are removed from vapors traveling through the vadose zone, the vapor quality should be monitored at discrete points throughout the affected vadose zone. Direct push probes, such as described in Section 3.2.2.1, can be used to collect subsurface pressure data and monitor the soil gas quality during sparging. In situ respiration tests are typically performed to estimate the extent of biodegradation within the vadose zone. In addition, while sparging is occurring, it is useful to monitor the oxygen and carbon dioxide concentrations at the vadose zone monitoring points to:

- ensure that sufficient oxygen (greater than approximately 5%) is present in the soil gas for biodegradation; and
- determine if carbon dioxide is present.

If less than 5% oxygen is present in the soil gas, it may be necessary to increase the sparging flow rates to supply more air to the subsurface for biodegradation. If, on the other hand, little (<1%) or no carbon dioxide is measured in the soil gas, the sparging flow may be too high, resulting in too short of a residence time in the vadose zone for biodegradation of the vapor contaminants.

6.4.5 Pulsed Operation

The theory and benefits of pulsed operation of an air sparging system are discussed in previous sections. With regard to performance monitoring of pulsed systems, the pulse duration and interval should be periodically monitored for effectiveness by measuring the contaminant concentration in the vapor extraction effluent (if such a system is used) or in the soil gas collected from vadose zone monitoring points (if a vapor extraction system is not used) at regular intervals during the pulse cycle. The objective is to estimate the amount of contaminants being removed from groundwater and into soil gas due to the sparging pulse.

If the soil gas or vapor extraction effluent contaminant concentrations remain high at the end of a pulse cycle, this may be an indication that a longer pulse would be more effective. This approach is only valid if no substantial vadose zone contamination remains, since the soil gas quality needs to be indicative of the contaminant mass being transported *from the aquifer*.

If vadose zone soils are contaminated, the pulse duration and interval may be evaluated by monitoring the transient mounding that occurs upon commencement of a pulse. In this case, the objective would be to modify the pulse cycle to coincide with the time to form and then collapse the groundwater mound around a particular sparging well.

6.4.6 Effectiveness and Rebound Monitoring

Bass (1998) presented a review of case studies to shed light on how well air sparging achieves permanent reduction in groundwater contaminant concentrations. They also compiled basic design features that were used in the case studies. Tables 6.1 and 6.2 summarize 21 sparging sites (6 chlorinated solvents, 15 petroleum hydrocarbons). Soils ranged from silt to coarse sand and gravel, with both native and backfilled material as the sparged matrix. Sparging well spacing ranged from 3.5 to 24 m (12 to 80 ft), and flow rate per sparging well from 3 to 35 scfm. Some of the systems injected sparging air continuously, others used pulsed operation. Well systems ranged from 1 to 16 wells and included both horizontal and vertical types. Durations of sparging system operation ranged from a few months to more than four years.

In each case study, groundwater concentrations were compared before sparging was initiated, just before sparging was terminated, and in the months following shutdown of the sparging system. Post shutdown monitoring data are available for only a few months in most cases, but at some sites more than a year of post shutdown data have been collected. While this is a limited database, examination of the characteristics and behavior of the sparging study sites in Tables 6.1 and 6.2 lead to the following insights presented by Bass (1998).

6.4.6.1 Petroleum-Contaminated Sites vs. Chlorinated Sites

Only 30% of the chlorinated sites rebounded, while about 50% of the petroleum sites rebounded. The magnitude of the rebound at the chlorinated sites was also considerably smaller than at the petroleum sites. Groundwater contaminant concentrations initially decreased during sparging by 1 to 4 orders of magnitude, but when rebound occurred (especially at the petroleum sites), contaminant concentrations increased several orders of magnitude again after sparging was terminated so that the overall reduction was less than an order of magnitude.

6.4.6.2 Factors Affecting Rebound

In general, the more successful sparging systems had air flow rates greater than 10 scfm/well, and well spacings less than 6 m (20 ft). The successful systems addressed the entire source area. Sparging systems that achieved a significant reduction in groundwater concentrations, but rebounded when the system was shut off, were characterized by a low sparging air flow rate, a low sparging well density, and/or a failure to address the entire source area.

As shown in Figure 6.1, low flow and large well spacing were generally associated with more rebound. The greater the spacing, the greater the air flow required to achieve a permanent reduction in groundwater contaminant levels. An interesting exception to this trend was the behavior of several chlorinated sites. These sites had well spacing on the order of 24 m (80 ft) but showed no rebound. The possible explanation is that these sites had only dissolved contaminants.

Table 6.1
Air Sparging Sites with Post-Closure Rebound

Site Specifics	Duration (months)		Contaminant	Contaminant Concentration (µg/L)			Comments
	Sparging	Post-Closure		@ Start	@ Shutdown	Post-Closure	
Site #1 (CA) Industrial 16 sparge wells ≈ 50 ft spacing 12 scfm/well Pulsed (daily cycle)	3.5	7.5	Solvents				Well graded fine sand; WT has risen by 10-20 ft
			• 1,1,1-TCA	2,200	33	41	Downgradient monitoring well
				24	6	<5	Downgradient monitoring well
			• 1,1-DCE	190	<5	9.9	Downgradient monitoring well
				14	<5	17	Crossgradient well; 6.7 ppb after 5 months
Site #2 (NJ) Service station 3 sparge well ≈ 20 ft spacing 5 scfm/well Pulsed (2 week cycle)	21	10	Weathered gas				Tight silty sand; excavated soils returned to tank pit; significant drop in water table
			• Benzene	580	78	290	120 µg/L 4 months after sparge system shutdown
				5	2	21	4 µg/L 4 months after sparge system shutdown
				180	57	21	12 µg/L 4 months after sparge system shutdown
				2,200	150	690	150 µg/L 4 months after sparge system shutdown

			• Total BTEX	17,000	592	23,590	3,930 µg/L 4 months after sparge system shutdown
				68	6	147	27 µg/L 4 months after sparge system shutdown
				1,800	346	1,617	77 µg/L 4 months after sparge system shutdown
				31,000	2,610	21,190	1,900 µg/L 4 months after sparge system shutdown
Site #3 (CT) Service station 4 sparge wells ≈ 50 ft spacing 5 scfm/well Continuous flow	21	10	Gasoline, diesel				Fine sand; shut down when system struck by car
			• Benzene	SPHC	94	78	Source area monitoring well
				SPHC	930	810	Source area monitoring well
				SPHC	3,700	1,400	Source area monitoring well
				380	830	510	Downgradient monitoring well
			• Total BTEX	SPHC	1,376	325	Source area monitoring well
				SPHC	2,365	1,508	Source area monitoring well
				SPHC	7,310	9,470	Source area monitoring well
				SPHC	376	9	Source area monitoring well
				400	8	23	Upgradient area monitoring well
				3,300	1,773	1,961	Downgradient area monitoring well
			• TPH	SPHC	32,000	7,000	Source area monitoring well
				SPHC	7,100	560	Source area monitoring well
				SPHC	28,000	20,000	Source area monitoring well
				SPHC	15,800	2,310	Source area monitoring well

Table 6.1 (cont.)
Air Sparging Sites with Post-Closure Rebound

Site Specifics	Duration (months)		Contaminant	Contaminant Concentration (µg/L)			Comments
	Sparging	Post-Closure		@ Start	@ Shutdown	Post-Closure	
Site #4 (NY) Service station 4 sparge wells ≈ 30 ft spacing 13 scfm/well Pulsed (daily cycle)	12	16	Weathered gas				Medium sand; pulsing began 3 months before shutdown; some areal installation limitations
			• Benzene	1,800	< 0.5	210	< 0.3 µg/L 2 months after shutdown; source area
				15	< 0.5	1	7 µg/L 2 months after shutdown; source area
				8*	0.5	12	8 µg/L 2 months after shutdown; downgradient
				< 0.5*	< 0.5	15	25 µg/L 2 months after shutdown; downgradient
				< 0.5*	< 0.5	37	< 0.5 µg/L 2 months after shutdown; downgradient
			• Total BTEX	53,200	7	21,810	2,670 µg/L 2 months after shutdown; source area
				2,357	< 5	14	35 µg/L 2 months after shutdown; source area
				3,668*	333	358	808 µg/L 2 months after shutdown; downgradient
				7,830*	42	625	227 µg/L 2 months after shutdown; downgradient
				12*	< 5	3,147	5 µg/L 2 months after shutdown; downgradient

Site #5 (CT) Service station 2 sparge wells ≈ 40 ft spacing 3.5 scfm/well Pulsed (daily cycle)	17	4	Weathered gas				Tight soil; pilot system only
			• Benzene	2,000	32	120	Source area monitoring well
				9,400	160	–	Source area monitoring well
				7	17	2	Source area monitoring well
				27	2	4	Crossgradient monitoring well
				5	3	22	Downgradient monitoring well
			• Total BTEX	76,000	2,300	26,000	Source area monitoring well
				119,000	11,000	–	Source area monitoring well
				68	300	4	Source area monitoring well
				200	11	5	Crossgradient monitoring well
				660	84	2,400	Downgradient monitoring well
Site #6 (WA) Service station 3 sparge wells 30 ft spacing 4 scfm/well Pulsed (≈ 4 week cycle)	21	2	Fresh gasoline				Sparged in tank pit surrounded by tight soil
			• Benzene	11,000	<0.3	6	Within tank pit
				2,200	<0.3	71	Within tank pit
				22	<0.3	<0.3	Outside tank pit
			• Total BTEX	37,800	6	1,054	Within tank pit
				12,170	4	1,566	Within tank pit
				114	<2	<2	Outside tank pit
			• TPH	82,000	87	10,000	Within tank pit
				52,000	60	21,000	Within tank pit
				1,000	< 10	< 10	Outside tank pit
				2,000	< 10	< 10	Outside tank pit

Table 6.1 (cont.)
Air Sparging Sites with Post-Closure Rebound

Site Specifics	Duration (months)		Contaminant	Contaminant Concentration (µg/L)			Comments
	Sparging	Post-Closure		@ Start	@ Shutdown	Post-Closure	
Site #7 (DE) Dry cleaning 15 sparge wells ≈ 40 ft spacing 10 scfm/well Continuous flow	7.5	2	Solvents				Permeable sand
			• PCE	20,000	74	140	Source area monitoring well
				2,700	85	46	Downgradient monitoring well
				134	23	33	Downgradient monitoring well
			• TCE	11,000	260	460	Source area monitoring well
				1,800	15	73	Downgradient monitoring well
				10,000	370	650	Source area monitoring well
			• DCE	2,200	15	130	Downgradient monitoring well
Site #8 (NY) Service station 14 sparge wells ≈ 20 ft spacing 8 scfm/well Continuous flow	3.5	2	Weathered gas (> 2,000 gal)				Down for repairs; water table rise after shutdown
			• Benzene	83	120	34	Source area monitoring well
				55	< 0.5	< 0.5	Source area monitoring well
				1,500	350	2,300	Source area monitoring well
				7	2	< 0.5	Source area monitoring well
				86	< 0.5	< 0.5	Downgradient monitoring well
				33	9	34	Downgradient monitoring well

			• Total BTEX	964	1,779	622	Source area monitoring well
				2,575	4	4	Source area monitoring well
				3,270	1,920	11,900	Source area monitoring well
				65	35	70	Source area monitoring well
				2,906	<5	<5	Downgradient monitoring well
				102	549	12,434	Downgradient monitoring well
Site #9 (CA) Service station 9 sparge wells ≈ 20 ft spacing Pulsed (12 hr cycle) Initiated 7/93	21	1	Weathered gas				Sand; some of source plume may be under building
			• Benzene	1,000	34	210	Source area monitoring well
				680	53	14	Source area monitoring well
			• Total BTEX	2,760	425	245	Source area monitoring well
				1,081	102	263	Source area monitoring well
			• TPH as gasoline	9,400	510	2,500	Source area monitoring well
				3,400	130	120	Source area monitoring well

*Initial analysis date was about 5 months after the start of sparging.

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Table 6.2
Air Sparging Sites without Post-Closure Rebound

Site Specifics	Duration (months)		Contaminant	Contaminant Concentration (µg/L)			Comments
	Sparging	Post-Closure		@ Start	@ Shutdown	Post-Closure	
Site #1 (WI) Industrial 3 sparge wells ≈ 80 ft spacing 10 scfm/well Pulsed (4 hr cycle)	14	4	Solvents				Addresses source area; began pulsing after 7 months
			• TCE	670	9.9	5.7	Source area monitoring well
				17	0.95	1.6	Downgradient monitoring well
Site #2 (WI) Industrial 5 sparge well ≈ 80 ft spacing 10 scfm/well Pulsed (4 hr cycle)	10	4	Solvents				Addresses downgradient plume; began pulsing after 3 months
			• TCE	32	3.2	1.5	
				99	12	3.7	
				8.3	0.66	0.52	
				160	25	14	
Site #3 (IN) Industrial 11 sparge wells ≈ 50 ft spacing 15 scfm/well Continuous flow	18	4	Solvents				Sand and gravel
			• 1,1,1-TCA	4,000	34	15	Source area monitoring well
				260	12	3	Downgradient monitoring well
			• DCE, DCA	720	13	12	Source area monitoring well
				134	12	7	Downgradient monitoring well

Site #4 (MA) Industrial 3 sparge wells 80-150 ft spacing 18 scfm/well Continuous flow	7	1.5	Solvents				Sand; wells placed in non-contiguous pockets of contamination; crossgradient well operated only 2 months
			• 1,1,1-TCA	200	–	9.3	Downgradient monitoring well
				14	–	5.8	Crossgradient monitoring well
			• 1,1-DCE	27	–	2.0	Downgradient monitoring well
			• PCE	8.9	–	6.0	Crossgradient monitoring well
Site #5 (NY) Service station 7 sparge wells ≈ 12 ft spacing 13 scfm/well Continuous flow	15	1	Gasoline				
			• Total BTEX	18,500	<5	<5	Source area monitoring well
			• TPH	32,000	<100	<100	Source area monitoring well
				5,600	<100	<100	Downgradient monitoring well
Site #6 (MA) Service station 1 sparge well 35 scfm Continuous flow	11	2	Fresh gasoline				Uniform sand
			• Total BTEX	4,000	8	26	Source area monitoring well
				1,000	1,2500	331	Source area monitoring well
				5,300	1,770	117	Source area monitoring well
				190	474	38	Downgradient monitoring well
				640	436	106	Downgradient monitoring well
				770	<5	<5	Source area bedrock monitoring well

Table 6.2 (cont.)
Air Sparging Sites without Post-Closure Rebound

Site Specifics	Duration (months)		Contaminant	Contaminant Concentration (μg/L)			Comments
	Sparging	Post-Closure		@ Start	@ Shutdown	Post-Closure	
Site #7 (NY) Service station Horizontal wells 90 scfm total Continuous flow	17	10	Gasoline				Nutrients added to fine sands, returned to tank pit
			• Total BTEX	14,000	480	8	Source area monitoring well
				90	330	290	Source area monitoring well
				24	1	1	Crossgradient monitoring well
Site #8 (NH) Service station 8 sparge wells ≈ 20 ft spacing 3 scfm/well Pulsed (daily cycle)	49	8	Weathered gas				Medium sand; 5 wells installed after 11 months to address upgradient source (which continues)
			• Benzene	70	<0.4	70	Source area monitoring well
				1,400	500	–	Source area monitoring well
				79	3.5	160	Downgradient well (≈ 75 ft from sparge system)
				SPHC	<2	–	Crossgradient monitoring well; near off-site source
				SPHC	<1	–	Upgradient monitoring well; near off-site source
			• Total BTEX	5,470	3,260	3,651	Source area monitoring well
				1,269	13,300	3,380	Downgradient well (≈ 75 ft from sparge system)
Site #9 (MA) Service station 5 sparge wells ≈ 13 ft spacing 2.5 scfm/well	19	10	Gasoline				Some excavation of source area
			• Total BTEX	480	BDL	BDL	123 μg/L 5 months after shutdown; downgradient well

Site #10 (FL) Service station 6 sparge wells 6 scfm/well ≈ 45 ft spacing Continuous flow Initiated 1/95	3	1	Weathered gas				60 ft depth to water; sandy; no product reached water table, so plume is purely dissolved phase
			• Benzene	2,175	–	<0.5	
				183	–	<0.5	
				481	–	<0.5	
			• Total BTEX	13,068	–	<0.5	
				788	–	<0.5	
Site #11 (NH) Fueling station 7 sparge wells 5 scfm/well ≈ 20 ft spacing Pulsed (12 hr cycle) Initiated 7/93	21	1	Gasoline				Fine/medium sand; sparge wells set 10 ft in groundwater at top of silt layer
			• Benzene	510	5.0	1.0	Source area monitoring well
				110	10	7.8	Source area monitoring well
				420	<2.5	4.6	Downgradient monitoring well
				28	3.0	6.5	Crossgradient monitoring well
			• Total BTEX	37,110	4,355	2,074	Source area monitoring well
				36,410	13,910	5,338	Source area monitoring well
				9,948	1,524	340	Downgradient monitoring well
Site #12 (FL) Gas/diesel USTs 1 sparge well 10 scfm/well Pulsed (1-2 hr cycle) Initiated 3/95	2	0.75	Gasoline/diesel				Sand; source area of limited extent (20 ft square)
			• Total BTEX	5,322	110	115	Source area monitoring well

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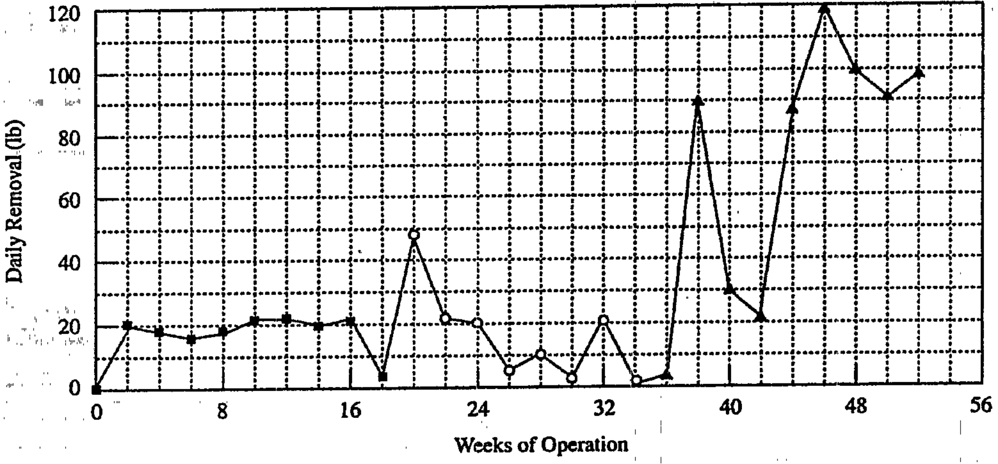
Figure 6.1
Impact of Pulsing on Performance



■ Vent Only (Week 0-18)
○ Continuous Sparging (Week 18-36)
▲ Pulsed Sparging (Week 36-52)

Mass removal rates were greatly improved by pulsed sparging after venting only and continuous sparging had been implemented.

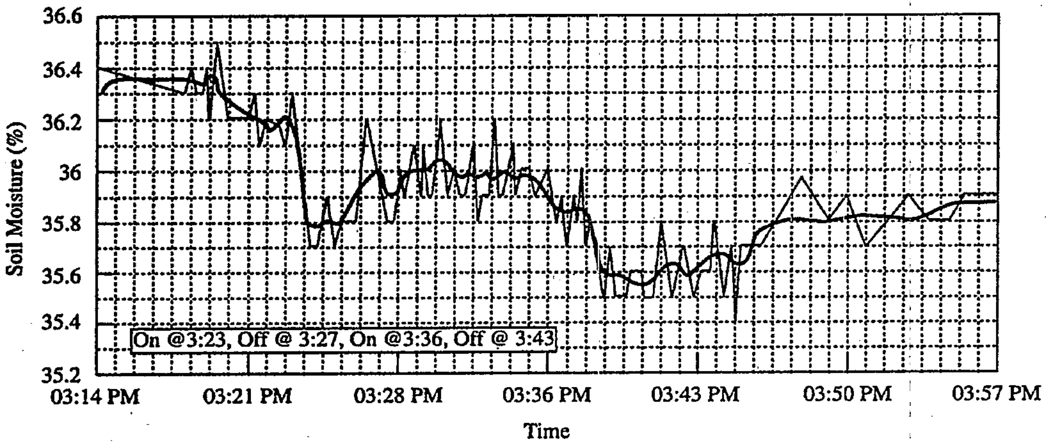
Reprinted from *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes*, W.S. Clayton, R.A. Brown, and D.H. Bass, "Air sparging and bioremediation: the case for in situ mixing", 1995 with permission of Battelle Press.

Figure 6.2 shows the effect of flow and the number of wells. Generally, the more wells and the higher the flow, the better performance of the system. Although increasing the number of wells would seem to allow for reduced flow, the opposite is true; as the number of wells increases, so do the flow requirements per well. The well density, rather than the absolute number of wells, is the more likely important parameter.

6.4.6.3 Dissolved-Phase Plumes vs. Source Areas

There was a 70% rebound rate in systems treating the source area as compared to only a 28% rebound rate in systems treating a dissolved groundwater plume. The dissolved-phase plumes that did rebound were generally associated with sites having a large or highly-contaminated source area that was not fully removed prior to sparging. When the released petroleum did not contact the groundwater to create a smear zone of adsorbed product, remediation by sparging was more effective even with less aggressive sparging systems. For example, in Site 9 (Table 6.2), where the source area had been excavated, no rebound was observed even though the flow rate per sparging well was only 2.5 scfm. In Site 10 (Table 6.2), where the released product did not extend downward through the entire 18 m (60 ft) deep vadose zone, remediation was rapid despite a 14 m (45 ft) well spacing.

Figure 6.2
TDR Response to Pulsed Injection
(3 m radius @ injection depth)



Time series moisture content data collected during pulsed sparging shows a distinct response to each air injection pulse, increasing the displacement of groundwater and improving mixing.

Reprinted from *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes*, W.S. Clayton, R.A. Brown, and D.H. Bass, "Air sparging and bioremediation: the case for in situ mixing", 1995 with permission of Battelle Press.

6.4.7 Health and Safety Monitoring

An industrial hygienist should be responsible for reviewing compliance with health and safety requirements during operation of the air sparging system. The site should have a health and safety plan prepared in accordance with OSHA and all other applicable standards. At a minimum, the plan should address the following.

- Contaminant characterization
- Hazard/risk analysis
- Staff organization and qualifications
- Training
- Personal protective equipment
- Medical surveillance
- Exposure monitoring
- Heat/cold stress monitoring
- Standard operating safety procedures
- Site control measures
- Personal hygiene and decontamination
- Emergency equipment and first aid requirements
- Emergency response and contingency procedures
- Accident prevention
- Logs
- Reports
- Record keeping

6.5 Operational Modifications to Enhance Performance

Section 5.4 presents the modifications that can be made during the design stage to enhance the mass extraction rate of an air sparging system. If an operating system does not produce acceptable contaminant concentrations at compliance monitoring points, the following operational controls can be adjusted as necessary:

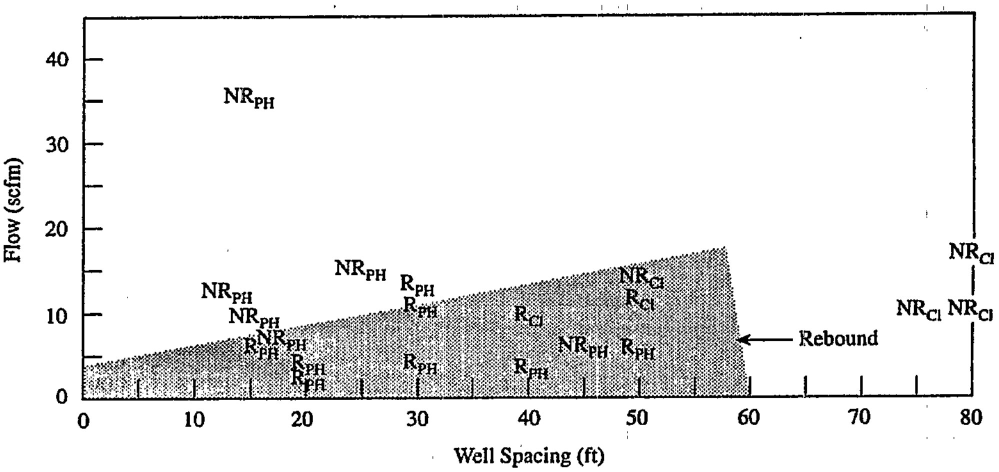
- *air sparging wells*-on/off, air injection pressure, air flow, pulsing, balancing with other wells in network;
- *air compressor*-pressure setting, manifold pressure setting, main air flow control valve to manifold;
- *manifold*-total air flow to well network, operating pressure, well selection (partial on, on/off), backflushing of air lines to remove condensation; and
- *monitoring points*-monitor impact of any change made in operating scheme and record influence and result in log book.

By adjusting these parameters, the operator can create conditions that favor an even distribution of air to the impacted zone. The ultimate criteria for assessing the effectiveness of any system modifications are typically attainment of acceptable contaminant concentrations at the compliance monitoring points and achieving an acceptable mass removal rate. Further operational changes and adjustments are discussed in Section 6.3.1.

6.6 Quality Control

The general quality control issues that pertain to operation of an air sparging system are very similar to those described for vapor extraction systems in Section 4.6 (see Figures 6.3 and 6.4).

Figure 6.3
Rebound as a Function of Flow and Well Spacing



NR	No Rebound
R	Rebound
PH	Petroleum Hydrocarbon
Cl	Chlorinated

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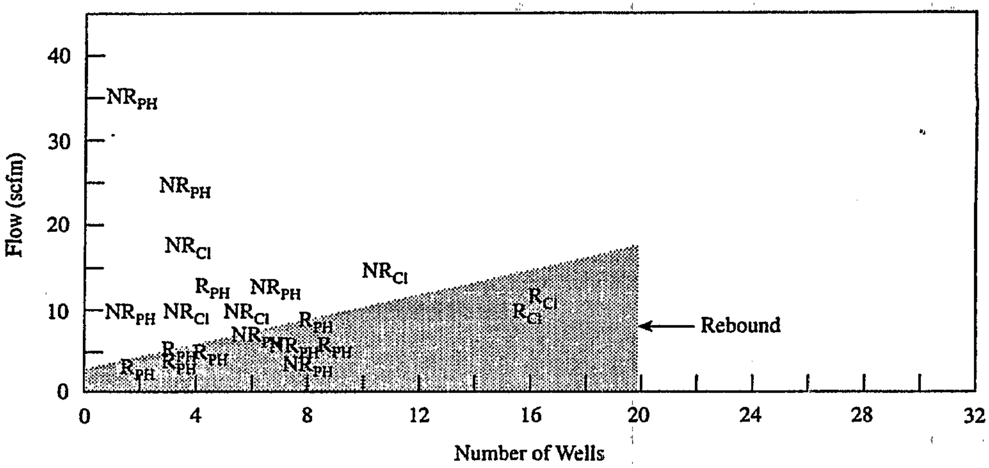
Figure 6.4
Rebound as a Function of Flow and Number of Wells



NR	No Rebound
R	Rebound
PH	Petroleum Hydrocarbon
Cl	Chlorinated

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7

CASE HISTORIES

Case 1 — Petroleum Distribution Facility in Sparks, Nevada

General Site Information

Name: Petroleum Distribution Facility

Location: Sparks, Nevada

Remediation Contractor: Camp, Dresser & McKee, Inc., Reno/Denver

Regulatory Factors

Authority

Nevada Division of Environmental Protection, US EPA

Requirements/Cleanup Goals

Control contaminant sources; recover free product; no further degradation of groundwater

Results

After one year of operation, the remediation system had removed approximately 1.27 million kg (2.8 million lb) of contaminants as follows:

- 256,000 kg (564,000 lb) removed via vapor extraction;
- 1,013,000 kg (2,233,000 lb) removed via aerobic biodegradation enhanced by vapor extraction;

- 480 kg (1,055 lb) removed via groundwater extraction/treatment; and
- 545 (1,200 lb) removed as free product.

Remediation is ongoing.

Operation

Type

Full-scale remediation

Period

November 1995 - ongoing

Waste Characteristics

Source

Leaking aboveground and underground storage tanks and surface spillage

Contaminants

Gasoline, diesel fuel, aviation fuel, and lesser amounts of chlorinated ethenes and ethanes

Type of Media Treated

Sandy soils and groundwater

Quantity of Media Treated

Approximately 0.91 million m^3 (1 million $yd^{3)}$ of soil over 127 acres. Approximately 757 million L (200 million gal) of groundwater.

Technology

Description

The remedial system is comprised of:

- 30 combination groundwater and vapor extraction wells;
- two thermal oxidation units with a combined capacity of 9,000 ft^3/min;
- fluidized bed biological reactors;
- oil-water separator; and
- mobile free product recovery trailer.

Cost Data

Remediation is still in progress.

Case 2 — NYSDEC, Bioventing of Chlorinated VOCs in Sweden, NY

General Site Information

Name: Sweden-3 Chapman Site

Location: Sweden, New York

Owner: Confidential

Owner Contact:

Nick Kolak, Ph.D.
New York State Department of Environmental Conservation
Albany, NY
(518) 475-3372

Remediation Contractor:

Peter J. Cagnetta, CPSSc
R. E. Wright Environmental, Inc.
3240 Schoolhouse Road
Middletown, PA 17057

Project Description

As part of the US EPA Superfund Innovative Technology Evaluation program, R. E. Wright constructed a bioventing system to decontaminate glacial till soil containing trichloroethene (TCE) and 1,2-dichloroethene (DCE). The system consisted of 30 soil gas extraction wells manifolded to the vacuum port of a 5-horsepower positive displacement blower and 30 gas-phase amendment injection wells manifolded to the discharge port of the blower unit. A timer controlled the periodic extraction of soil gas from the soil. When operating in the injection mode, anhydrous ammonia and methane were injected into the injection air stream and into the subsurface. Within five months of treatment, the concentrations of TCE and 1,2-DCE have declined significantly below the cleanup goals. Mass balance calculations indicated that 80% of the initial mass of TCE had been biodegraded, and 12% had been vapor extracted. 914.4 m^3 (1,000 yd^3)of soil was treated using this process. The use of this technology for site-wide remediation of 9,144 m^3 (10,000 yd^3) of soil is pending.

Regulatory Factors

Authority

New York State Department of Environmental Conservation (NYSDEC)

Requirements/Cleanup Goals

TCE	1,500 micrograms per kilogram (µg/kg)
1,2-DCE	600 µg/kg

Results

- NYSDEC soil cleanup goals achieved for TCE and 1,2-DCE within five months.
- 92% reduction in TCE mass (80% biodegraded and 12% vapor extracted).
- Mean TCE soil concentration declined from 4,900 µg/kg to 56 µg/kg.

Operation

Type

Large-scale demonstration pilot

Period

July 1994 to December 1994

Waste Characteristics

Source

Improper disposal of drums containing industrial solvents

Contaminants

TCE	4,960 milligrams per kilogram (mg/kg)
1,2-DCE	610 mg/kg

Type of Media Treated

USDA texture — loam, glacial till

Quantity of Media Treated

914.4 m^3 (1,000 yd^3)

Technology

Description

In situ bioventing consisting of soil gas extraction wells and gas-phase amendment injection wells. Methane, oxygen, and anhydrous ammonia injected to stimulate indigenous microorganisms. Blower unit operated in timed extraction/injection cycle.

Significance

Remediated chlorinated solvent-impacted soil using indigenous microorganisms and conventional vapor extraction equipment and wells. Rigorous US EPA quality assurance/quality control oversight independently confirmed successful results.

Cost Data

Total project cost of $136,900 included design, construction, operation, and closure. A comprehensive sampling and analysis program was implemented throughout the project to quantify the decreases of TCE and 1,2-DCE in soil and identify the primary removal mechanism (bioremediation).

Case 3 — PECO Energy Company, Bioventing of Diesel-Range Hydrocarbons and 1,1,1-TCA in Philadelphia, Pennsylvania

General Site Information

Name: PECO Energy Company — Oregon Maintenance Shop

Location: Philadelphia, Pennsylvania

Owner: PECO Energy Company

Owner Contact:

Mr. Fred Gloeckler, P.E.
PECO Energy Company
Philadelphia, PA
(215) 841-4660

Remediation Contractor:

Gregory J. Burgdorf, P.G.
R. E. Wright Environmental, Inc.
3240 Schoolhouse Road
Middletown, PA 17057

Project Description

Approximately 7,711 tonne (8,500 ton) of in-place soil were impacted by predominantly diesel-range hydrocarbons and a smaller quantity of 1,1,1-trichloroethane (TCA). The impacted soil was located within the facility storage area and was caused by accidental releases from aboveground storage vessels. After pilot testing and system design, remediation activities were initiated in June 1994. 1,1,1-TCA and the volatile hydrocarbons were removed from the ground via vapor extraction. At system start-up and periodically throughout treatment, the subsurface was amended with nutrients essential for bacterial growth and a surfactant to enhance the biodegradation of the less volatile hydrocarbons. Formal state-approved closure was granted in October 1996.

Regulatory Factors

Authority

Pennsylvania Department of Environmental Protection

Requirements/Cleanup Goals

Total Petroleum Hydrocarbons (TPH)	1,000 mg/kg
1,1,1-TCA	1 mg/kg

Results

- Treatment of Area 1 (5,897 tonne [6,500 ton]) completed in 6 months of operation.
- Treatment of Area 2 (1,814 tonne [2,000 ton]) completed in 12 months of operation.
- Treatment of all soil completed for approximately $30/ton.

Operation

Type

Full-scale site-wide system

Period

June 1995 to May 1996

Waste Characteristics

Source

Accidental releases from aboveground storage vessels

Contaminants

TPH	25,000 mg/kg
1,1,1-TCA	1,500 mg/kg

Type of Media Treated

USDA texture — sandy loam

Quantity of Media Treated

7,711 tonne (8,500 ton)

Technology

Description

In situ bioventing consisting of nine vapor extraction wells manifolded to a 5 hp 500 ft^3/min regenerative blower and three vapor extraction wells manifolded to a 3 hp 200 ft^3/min regenerative blower. Each skid-mounted blower unit was equipped with a moisture knockout tank and vapor-phase granular-activated carbon unit.

Significance

Remediated soil in-place so that daily activities at the site could continue. Significant cost savings were realized by in situ treatment versus excavation and off-site treatment/disposal.

Cost Data

The total bioventing project cost of $275,000 included pilot testing, design, construction, operation, and closure.

Case 4 — Two Air Sparging Case Studies

This section presents observations by the monograph Task Group from two sparging case studies. While similar results have been observed at other sparging sites, these two were selected as representative.

Case Study 4A

In Case Study 4A, a release of perchlorethylene (PCE) through floor drains underneath building resulted in vadose zone contamination and development of a dissolved-phase plume.

During the site investigation, the soil was logged by a geologist on 0.6 m (2 ft) intervals and classified as a clean, fine- to medium-grained sand with depth to water at about 10.6 m (35 ft) below ground surface. A sieve analysis on selected samples confirmed the field description. Based on pump tests, the soil hydraulic conductivity was $1 \bullet 10^{-2}$ cm/sec. During the site investigation, there was no indication of field-scale heterogeneity.

Vapor extraction was implemented for several months to remove PCE from the vadose zone soil underneath the building and to prevent further contaminant loading to the groundwater. A 30-day groundwater sparging pilot test was then conducted.

One groundwater sparging well was installed through the building floor and screened from 7.6 to 8.2 m (25 to 27 ft) below the water table. Two monitoring piezometer nests were installed at horizontal distances of 3 to 6 m (10 to 20 ft) from the sparging well. Within each nest, one piezometer was screened from 2.4 to 3 m (8 to 10 ft) below the water table, and the other from 5.5 to 6 m (18 to 20 ft) below the water table. Figure 7.1 shows the system layout.

For most of the sparging pilot test, the system was operated for 4 hours per day at a 10 scfm flow rate. Groundwater samples collected from each piezometer about every 5 days were analyzed for PCE. The piezometers were also monitored for pressure buildup or bubbling, either of which might have suggested that injected air was short-circuiting through the piezometers. Pressure buildup or bubbling was not detected. The changes in dissolved-phase PCE concentrations during and after the pilot test are shown in Figure 5.1.

In Case Study 4B, a large release of petroleum solvents resulted in both vadose zone and groundwater contamination. The groundwater was about 4.6 m (15 ft) below ground surface. After 555 L (150 gal) of floating NAPL were recovered, contamination in the source area still included NAPL at residual saturation 1 m (3.28 ft) above and below the groundwater table. An analysis of the NAPL showed it occupied about 20% of the saturated zone pore space in the affected area and consisted of mostly nonpriority pollutants such as hexane and mineral spirits. PCE, trichlorethylene (TCE), and other chlorinated solvents made up 1 to 2% of the NAPL. The NAPL was a continual source of VOC contamination in the groundwater.

The soil at the site was logged at numerous borings on 0.6 m (2 ft) intervals by a geologist and classified as a uniform, clean, fine- to medium-grained sand. The field analysis was confirmed by sieve analysis of selected samples. Based on slug test results, a $1 \bullet 10^{-2}$ cm/sec hydraulic conductivity was estimated.

A groundwater extraction and vapor extraction system was installed at the site. After 700 operating days, average VOC concentrations in the soil were less than 14 μg/kg (based on more than 100 soil samples collected vertically and horizontally throughout the target zone). After 4 years of operation, the groundwater extraction system had reached an asymptote of about 1,500 μg/L of total dissolved-phase VOCs in the groundwater discharge. Continual release of VOCs from the residual NAPL to the groundwater prevented further reduction in dissolved-phase concentrations.

A sparging system was then employed to directly contact the residual NAPL with a gas to better volatize the VOCs. Three sparging wells were installed in the source area around an operating groundwater extraction well. The sparging system was continuously operated for 5 months, during which time groundwater samples from the extraction well were analyzed monthly. Samples from the well were also analyzed bimonthly for several months before and after the sparging pilot test. The sparging system layout is shown in Figure 7.1, and the changes in the dissolved-phase VOC concentrations in water from the extraction well are shown in Figure 5.2.

Figure 7.1
Case Studies — Sparging System Layouts

CASE STUDY 4A

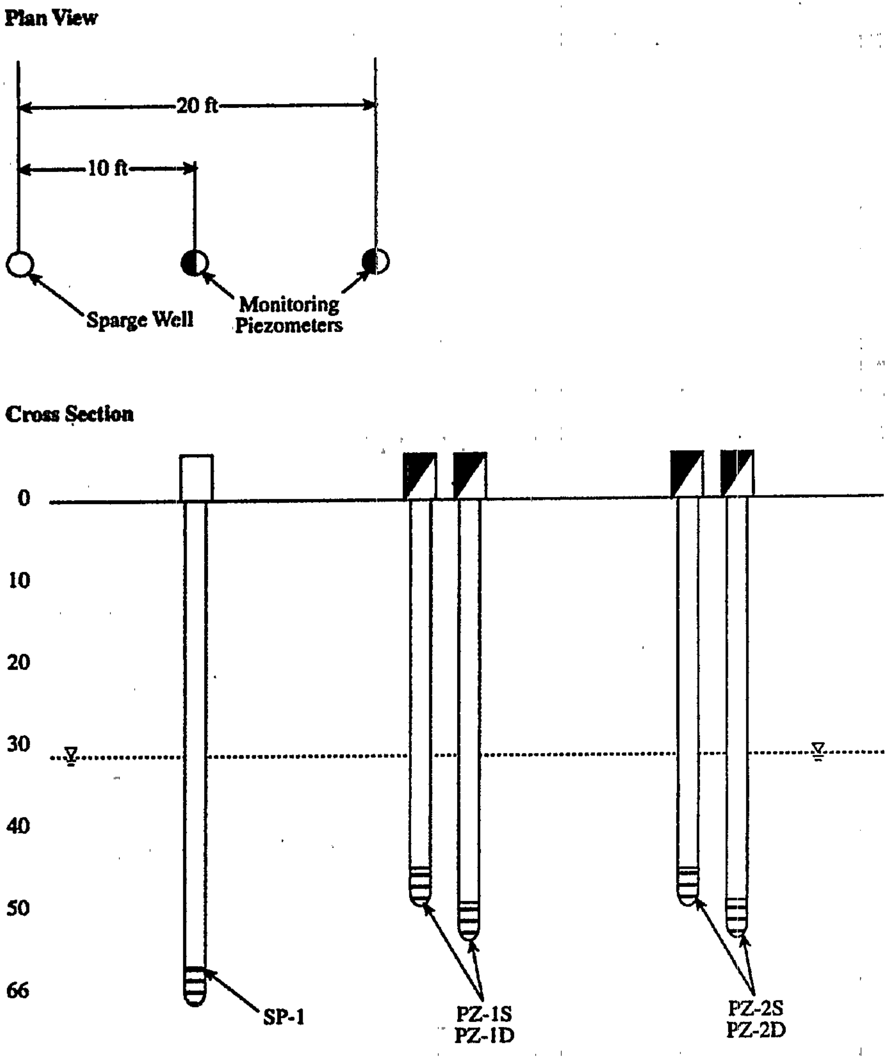

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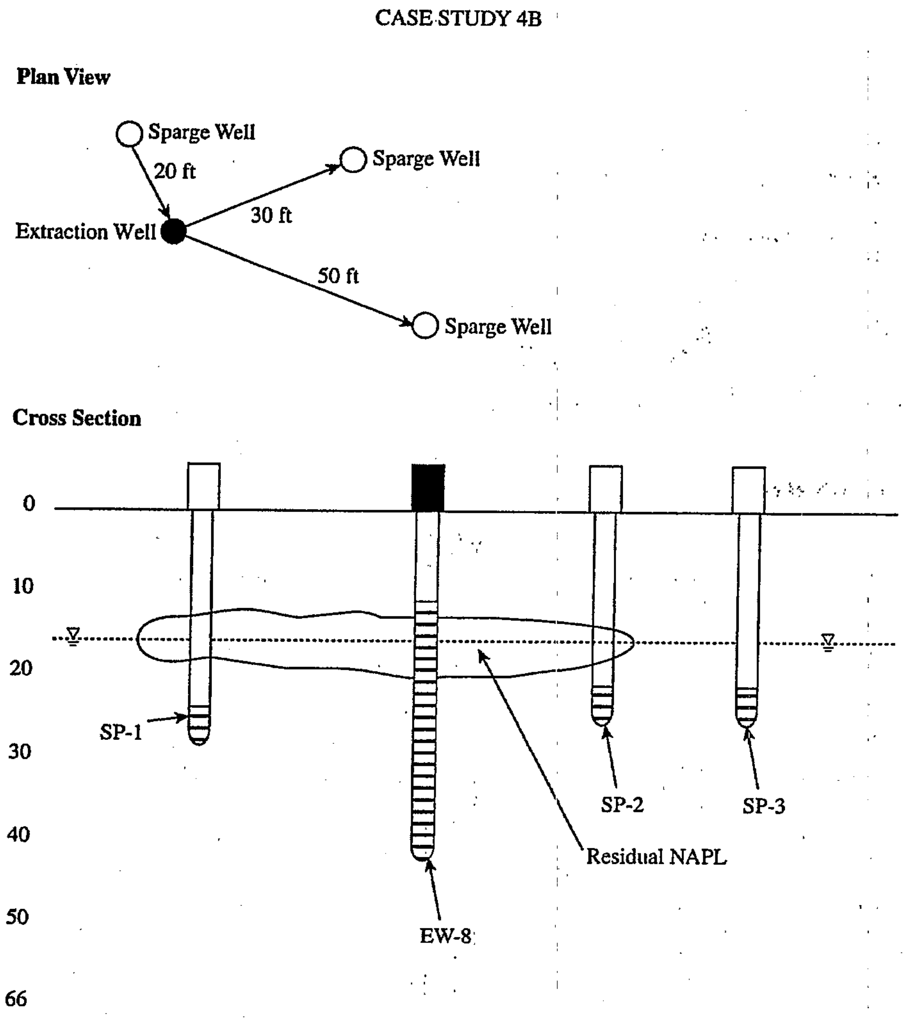
Figure 7.1 (cont.)
Case Studies — Sparging System Layouts



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Discussion

Monitoring Well Network Design and Reliability

Sparging-induced changes in dissolved-phase contaminants can be monitored with monitoring wells screened over 3 to 6 m (10 to 20 ft) of the aquifer, discrete piezometers screened over 0.3 to 0.6 m (1 to 2 ft) of the aquifer, and/or multilevel monitoring points installed with a geoprobe and each screened over a few inches.

The data from Case Study 4A (presented in Figure 5.1) suggest that the interpretation of sparging effectiveness may vary significantly depending on the type of monitoring system employed. The data from this site suggest removal efficiencies of 85% in the lower 4.6 to 7.6 m (15 to 25 ft) sparging zone and 15% in the upper 4.6 m (15 ft) sparging zone after 30 days of sparging.

It is believed that the building previously discussed (which prevents infiltration through the soil) and the degree of treatment achieved with the vapor extraction system immediately above the sparging system prevented continued contamination of the shallow groundwater. The lower treatment efficiency in the shallow groundwater is not attributed to new contamination in the shallow zone, but appears to be due to anisotrophy, and possibly pore-scale heterogeneity, which altered air flow pathways through this zone. Field-scale soil heterogeneity was not detected during continuous logging of the soil. Analysis based solely on monitoring wells screened over the upper 4.6 m (15 ft) of the aquifer would have resulted in an incomplete and inaccurate assessment of the sparging effectiveness at the site. Likewise, more vertically and horizontally spaced monitoring points might have resulted in a still more complex and varied picture of treatment effectiveness. In summary, vertical variations in treatment effectiveness were observed even through there were no observable changes in soil type or grain-size distribution.

Some data from monitoring wells and piezometers are suspect because of the potential for the wells or piezometers to become preferred-flow pathways for the sparged air (Johnson et al. 1993). The authors have observed this at some sites when injected air bubbles up through a monitoring point. In such cases, fairly rapid decline of dissolved-phase VOC concentrations would be expected since the VOCs in the wells would be quickly stripped. In these cases, a pressure of 1 to several centimeters of water can also be measured in the wells. The gradual decline of dissolved-phase VOC concentration presented in Figure 5.1, and the lack of detectable pressure in the wellhead, suggest that air flow is not short-circuiting through the piezometers at this site. Thus, these wells probably serve as good indicators of what is happening in the aquifer in their immediate vicinity.

Sparging in Residual NAPL vs. Dissolved-Phased Plumes

A main difference between Case Study 4A and Case Study 4B is that, at the former site, sparging was implemented in a dissolved-phase plume, while at the latter, sparging was implemented in an area of nonmobile, residual NAPL. Theoretical considerations and the post-sparging monitoring results at the two sites suggest that there may be significant differences in treatment potential and required duration for residual NAPL sites compared to those for dissolved-phase plume sites.

Within the dissolved-phase plume at Site 4A, a 50% overall reduction of dissolved-phase PCE was observed after 30 days of sparging. In the area of residual NAPL at Site 4B, there was a 50% reduction after 60 days of sparging and a 90% reduction in dissolved-phase VOCs after 150 days (as measured in samples collected from an operating groundwater extraction well within the sparging zone).

In the Site 4A dissolved-phase plume, post-sparging monitoring data indicated that dissolved-phase PCE concentrations were similar to those at the end of the sparging period (Figure 5.1). In the area of residual NAPL at Site 4B, post-sparging monitoring data indicated that dissolved-phase VOC concentrations increased to nearly the same level as before the test (Figure 5.2). After 5 months of sparging, the NAPL still provided further VOC loadings to the dissolved-phase plume.

The data suggest that sparging at residual NAPL sites may exhibit limitations similar to those observed with the groundwater extraction at residual NAPL sites (e.g., preferential fluid flow channels and contaminants needing to diffuse to those preferential flow channels). When air directly contacts a NAPL, the partitioning of VOCs into the air is relatively fast (as in the soil immediately adjacent to a sparging well). The rate-limiting step is likely VOC diffusion within the NAPL. However, with sparging, some or much of the NAPL more than 1.5 to 2 m (5 to 7 ft) from the sparging well may not directly contact the air. Thus, the VOCs still must diffuse into and through the water to an air channel. While a sparging system may be effective at treating the NAPL in the area where much of the water-filled porosity is converted to air-filled porosity, in areas farther from the sparging well where air channel density is lower, it will take much longer to treat residual NAPL.

The above discussion focuses primarily on contaminant volatilization. With time, it may be possible to biodegrade the residual NAPL as a result of oxygen transfer from the vapor phase into the dissolved phase. However, some of the same diffusion limitations for VOC mass transfer apply for oxygen mass transfer. There have been no conclusive estimates of oxygen transfer efficiency in sparging systems, but estimates have ranged from 0.05 to 0.5% (Boersma et al. 1993). In a conceptual cylinder 9 m (30 ft) in diameter, 4.6 m (15 ft) in length, with an average total petroleum hydrocarbon contamination of 2,000 mg/kg, and a sparging flow rate of 20 scfm, it would take 5 to 50 years to provide the stoichiometric requirements of oxygen for hydrocarbon biodegradation.

Recommendations

Based on these two case studies, the following recommendations are made for implementing sparging systems.

- First, given the typical anisotropy of even apparently uniform soil, vertically discrete groundwater monitoring points should be used with data from traditional monitoring wells to assess the performance of groundwater sparging systems. Anisotropy and pore-scale heterogeneities will cause vertical variation in treatment effectiveness.
- Second, spatial variations in treatment effectiveness around a groundwater sparging well suggest that the term “radius of influence” is misleading. A term such as “zone of sparging influence” is more accurate, and its use is recommended.
- Third, at most NAPL sites, a sparging system will probably have to operate for several years to volatilize and/or biodegrade the NAPL that is beyond the zone where 20-40% air saturation is achieved.

A

FIELD-SCALE PNEUMATIC PERMEABILITY MODELS

The purpose of this Appendix is to provide the reader with a comprehensive summary of existing analytical solutions for field scale determination of pneumatic permeability. This will assist in selection of an appropriate model for site-specific testing. The solutions are summarized in consistent nomenclature and variables to avoid confusion when comparing various solutions.

Field scale gas permeability testing originated in the petroleum industry for use in gas reservoir evaluation (Muskat and Botset 1931). However, over the past thirty or forty years soil scientists have conducted field scale air permeability tests to evaluate gas exchange between soils and the atmosphere, soil structure, and the movement of subsurface water as affected by simultaneous air movement. The advent of soil venting to remove or enhance biodegradation of hazardous organic compounds has hastened the development of analytical solutions for field scale gas permeability testing in the field of subsurface hydrology field over the past 10 years. Most of these solutions have been based on methods used in groundwater well hydraulics.

Air or pneumatic permeability tests typically involve the measurement of air flow in vapor extraction or air injection wells with concurrent measurement of pressure differential in surrounding vapor probes. Pneumatic permeability is then calculated using analytical solutions to selected governing partial differential equations. One approach to determine air permeability is to simply modify existing analytical groundwater solutions (Johnson, Kemblowski, and Colthart 1988, Johnson et al. 1990; Massman and Madden 1994; Beckett and Huntley 1994). Another example is the use of the groundwater hydraulics programs to analyze transient and steady-state pump test data. This approach is useful when there is a low pressure differential between the pumped well and the surrounding formation and an analytical gas permeability solution is not yet available for the boundary conditions incorporated in the groundwater solution. The error involved in this method should be small as long as pressure differential remains small. Falta (1996) points out that a drawback of this approach is that for some gas permeability problems there are no analogous groundwater solutions available. An example, which is quite common, is a gas permeability test performed in a formation open to the atmosphere. In this case, the atmosphere acts as a constant head boundary. Falta (1996) also states that there are basic differences in the nature of the test data collected during gas pump tests compared to groundwater tests. Groundwater test data often consist of transient drawdown data from a single observation well while gas pump test data often consist of steady-state pressure data from several observation locations. Measuring transient pressure in a gas pump test can be difficult in high permeability sands or gravels due to the rapidity (seconds) of establishment of steady-state gas flow conditions in media of high permeability. Considering that analytical solutions and software packages now exist which incorporate compressibility, partial penetration, constant pressure boundary conditions (atmospheric pressure) and flux boundary conditions (leakage through a confining layer), the use of groundwater flow equations to estimate pneumatic permeability is often not justified. AIR2D, a public domain model developed by Joss and Baehr (1995a), provides solutions for steady-state conditions and is available through the USGS. GASSOLVE developed by Falta (1996) provides solutions for transient conditions and is available from the developer upon request. When practical, transient tests are preferred over steady-state tests because numerous measurements can be collected at each vapor probe within the time frame of transient testing as opposed to just one measurement at each probe during steady-state testing. For media of high permeability such as sands, steady-state occurs under many circumstances (e.g., depth to well less than 15 ft) within seconds. For low permeability soils, however, such as clays and glacial till, steady-state may not occur for minutes or hours.

Another approach to pneumatic permeability determination is the use of numerical models. Numerical models, especially those specifically for gas flow such as AIR3D, which is a public domain modification of MODFLOW (finite-difference) developed by Joss and Baehr (1995b) for the USGS, are undoubtedly the most flexible methods of analyzing the gas pump test results. Initial and boundary conditions can be incorporated for problems which can not be solved analytically. Analytical methods are not suitable for analyzing numerous soil layers of various permeabilities, spatial variability within discrete layers, and site-specific anomalies (underground trenches for piping, etc.). Edwards and Jones (1994) provide an example of the use of finite-element numerical modeling to determine pneumatic permeability. Numerical models, however, should be used with caution. They are usually more computationally intensive than analytical solutions and are prone to truncation error in the hands of inexperienced users. However, the greatest limitation in using numerical models for gas pump test analysis is that adequate field data are rarely available to justify their use. The problem is inherently ill-posed. Falta (1996) states that unless a large amount of field data are available, the analysis of pump test data by fitting a numerical model is more likely to suffer from problems of nonuniqueness than the analysis of the data by fitting an analytical model. The problem of nonuniqueness means that a large number of data variations may produce a response similar to that observed in the field. This is due to the large number of unknown parameters (i.e., the permeability of each gridblock).

It is important for the reader to be aware of the numerous assumptions necessary to enable formulation of analytical solutions. Often, practitioners use gas permeability solutions without appreciation of these assumptions and, hence, do not realize the limitations and errors inherent in testing. Sometimes pneumatic permeability tests can be conducted to purposely minimize these errors. Identification and discussion of assumptions will be presented in the context of derivation of the governing partial differential equations for single-phase gas flow. The derivation starts with a discussion of basic fluid mechanics principles. This background is necessary to understand gas flow in porous media.

Quantitative evaluation of gas flow in porous media starts with development of a mass balance or continuity equation. The total mass *m* of a gas in a closed soil region is given by:

$$m = \iiint \theta\rho(x,y,z,t)dV \tag{A.1}$$

where: ρ = density of gas (M/L^3)
θ = volumetric gas content (L^3/L^3)

The rate at which mass increases is given by:

$$\frac{dm}{dt} = \iiint \theta \frac{\partial \rho}{\partial t} dV \tag{A.2}$$

If change in mass is due only to flow in and out of a closed soil region, then an alternative expression for (A.2) is:

$$\frac{dm}{dt} = -\iint (\rho \underline{q} \bullet \underline{n}) d \tag{A.3}$$

where: $\underline{q}$ = the darcy discharge vector (L/t),
$\underline{n}$ = normal vector.

By the divergence theorem, (A.3) is the same as:

$$-\iiint \nabla \bullet (\rho \underline{q}) dV \tag{A.4}$$

Equating (A.2) and (A.4) yields:

$$\iiint \theta \frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \underline{q}) \tag{A.5}$$

Thus, the continuity equation for single phase gas flow is:

$$\frac{\partial(\rho\theta)}{\partial t} + \nabla \bullet (\rho \underline{q}) = 0 \tag{A.6}$$

The continuity equation can be used with Darcy's Law, Bernoulli's Equation, and the Ideal Gas Law to formulate an equation for single-phase gas flow in porous media. If Darcy's Law is assumed valid for gas flow in a homogeneous, anisotropic media, then:

$$\underline{q} = -\frac{\rho g}{\mu} \underline{\underline{k}} \nabla H \tag{A.7}$$

where: g = acceleration due to gravity [L/t^2]
$\underline{\underline{k}}$ = gas permeability tensor [L^2]
H = total head [L]
μ = dynamic viscosity of gas [M/Lt].

Darcy's law is widely accepted as a valid approximation to the conservation of momentum principle for airflow in porous media at low Reynolds Number (Re) as defined by:

$$\mathrm{Re} = \frac{dq_m}{\mu\theta} \tag{A.8}$$

where: d = representative pore-space diameter [L]
q_m = specific mass flux [M/L^2-t].

Yu (1985) conducted column experiments to test the validity of Darcy's law for air flow through various-sized sands and showed that Darcy's Law was valid for Re <6.

One important assumption that is made in the use of Darcy's Law to describe airflow is that gas slippage or the Klinkenberg effect (Klinkenberg 1941) is negligible. The Klinkenberg effect is an enhancement of air phase permeability through slippage of air molecules along the boundaries of air-filled pores. Air flow along a pore wall is not zero as is assumed for laminar liquid flow. This occurs when the mean free path (distance between consecutive collisions or between the last collision and the pore wall) of air molecules approaches the dimensions of the pores (Dullien 1992). Thus, it occurs in small pores under low pressure or high vacuum. Therefore, the Klinkenberg effect is important when a vacuum is applied to soils having small, desaturated pores. Klinkenberg (1941) expressed this effect by:

$$k = k_\infty\left(1 + \frac{b}{P_m}\right) \tag{A.9}$$

where: k_∞ = a soil's "intrinsic" permeability [L^2]
b = a parameter of the porous medium [M/Lt^2],
P_m = mean pressure [M/Lt^2].

In this context, intrinsic permeability refers to the soil's permeability without consideration of the Klinkenberg effect. It includes consideration of relative permeability to air in the presence of soil-water. Thus, it is not an independent soil property as usually expressed in groundwater literature. The intrinsic permeability is obtained by plotting ($1/P_m$) versus k and extrapolating data to infinite pressure. The parameter b can be obtained by the slope of this straight line. Baehr and Hult (1991) demonstrate through calculations how omission of the Klinkenberg effect can result in errors >10% for soils having intrinsic permeabilities of less than 10^{-9} cm^2. Massmann (1989) related the relative importance of slip flow to viscous flow for low pressure systems. He calculated that materials with pore radii greater that 0.001 mm would exhibit minimal effects of slip flow relative to Darcy flow. Silt and clay materials often demonstrate pore radii of this magnitude. Incorporation of Equation A.9 introduces nonlinear terms that preclude the development of analytical solutions. Thus, it is typically ignored during pneumatic permeability testing.

Darcy's Law requires knowledge of the total head gradient. Bernoulli's Equation for a compressible fluid can be used to express the components of energy or head

$$H = z + \frac{v^2}{2g} + \frac{1}{g}\int_{P_o}^{P} \frac{dP}{\rho} \tag{A.10}$$

where: z = a vertical distance above an arbitrary datum [L]
v = velocity [L/T]
P = air pressure [M/LT^2]
P_o = a reference air pressure [M/LT^2].

If both the velocity and elevation contributions to total head are assumed negligible, total head can now be expressed as:

$$H = \frac{RT}{\omega g}\left[\ln P - \ln P_o\right] \tag{A.11}$$

where: R = universal gas constant [M-L^2/T^2-mol-T]
T = temperature [K]
ω = molecular weight of air [M/mole].

The assumption of a negligible component of velocity head may not be accurate near an extraction or injection well. The assumption of negligible elevation head may not be accurate for chlorinated contaminant laden air present at many hazardous waste sites under low gradient conditions. In Bernoulli's Equation, head is expressed as energy per unit weight. Terms on the right hand side of the equation represent the contribution of elevation, velocity, and pressure head respectively to total head. If it is assumed that the Ideal Gas Law is valid for gas flow under pressures typical of pneumatic permeability determination, gas density can be related to air pressure, temperature, and molecular weight by:

$$\rho = \frac{\omega P}{RT} \tag{A.12}$$

Darcy's law given in terms of its gas permeability tensor is:

$$\begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = \frac{\rho g}{\mu} \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \begin{bmatrix} -\partial H / \partial x \\ -\partial H / \partial y \\ -\partial H / \partial z \end{bmatrix} \tag{A.13}$$

where: $k_{xy} = k_{yx}$
$k_{xz} = k_{zx}$
$k_{yz} = k_{zy}$

In analytical gas permeability testing, it is assumed that site-specific coordinates are aligned with the principal axes of gas permeability. However, it must realized that this is done for mathematical convenience, specifically to allow development of analytical solutions, and that the actual principal directions of gas permeability may be quite different than that used for the model. This would become readily apparent if one injected a gas tracer and noted movement in a direction inconsistent with the head gradient. Analytical expressions for gas permeability are typically expressed in radial or cylindrical coordinates. If symmetry around a well is assumed, then

$$\begin{bmatrix} q_r \\ q_z \end{bmatrix} = \frac{\rho g}{\mu} \begin{bmatrix} k_{rr} & k_{rz} \\ k_{zr} & k_{zz} \end{bmatrix} \begin{bmatrix} -\partial H / \partial r \\ -\partial H / \partial z \end{bmatrix} \tag{A.14}$$

If alignment along the principal axes is assumed, then Darcy's Law for gas flow can be expressed as

$$\begin{bmatrix} q_r \\ q_z \end{bmatrix} = \frac{\rho g}{\mu} \begin{bmatrix} k_{rr} & 0 \\ 0 & k_{zz} \end{bmatrix} \begin{bmatrix} -\partial H / \partial r \\ -\partial H / \partial z \end{bmatrix} \tag{A.15}$$

Like alignment with the principal directions of permeability, symmetry is assumed for mathematical convenience. However, observation of asymmetric pressure or head distribution in the field is common especially in highly heterogeneous media such as glacial till.

Baehr and Hult (1991) substituted Equations A.7, A.11, A.12, and A.15 into A.6 and let $P^2 = \phi$ to yield:

$$\begin{aligned}\mu\phi\frac{1}{\sqrt{\phi}}\frac{\partial\phi}{\partial t} &= k_r\frac{\partial^2\phi}{\partial z^2} + \left(\frac{\partial k_r}{\partial r} + \frac{1}{r}k_r\right)\frac{\partial\phi}{\partial r} \\ &+ \left[2k_z\frac{\omega g}{RT} + \frac{\partial k_z}{\partial z} - k_z\left(\frac{1}{T}\frac{\partial T}{\partial z} + \frac{1}{\mu}\frac{\partial\mu}{\partial z}\right)\right]\frac{\partial\phi}{\partial z} \\ &+ \left[\frac{\omega g}{RT}\left(\frac{\partial k_z}{\partial z} - k_z\frac{1}{\mu}\frac{\partial\mu}{\partial z}\right) - 2k_z\frac{\omega g}{RT}\frac{1}{T}\frac{\partial T}{\partial z}\right]\phi\end{aligned} \tag{A.16}$$

In this derivation, they assumed that the molecular weight of air is constant and that:

$$\frac{\partial T}{\partial t} = 0 \quad \frac{\partial\theta}{\partial t} = 0 \quad \frac{\partial T}{\partial r} = 0$$

which, in words, means a steady temperature distribution, steady-state air-water distribution, and no variation in temperature with radial distance. Baehr and Hult (1991) state that natural areal temperature variations can be neglected over the scale of a pneumatic test. Also, temperature variations due to energy transport associated with induced air movement will be negligible as a result of the high thermal capacity of natural sediments and low-energy content of air. The assumption of constant volumetric air content, however, may impart a major error under aggressive operating conditions (e.g. high vacuum or pressure) in soils having a high moisture content. This is not a problem in well-drained soils such as coarse sands, but will likely be important in less permeable, more water saturated soils such as silts, clays, and glacial till. Redistribution of air and water during pneumatic testing can change the original spatial distribution of gas permeability. Vapor extraction will cause water to move towards the well while air injection will cause water to move away from the well. Thus, air extraction and air injection pneumatic tests may provide different estimates of pneumatic permeability. Another indicator of fluid redistribution during pneumatic testing is a notable change in air pressure and mass flow rate at the wellhead during testing. For instance, during sparging, where water is aggressively displaced from the vicinity of the well, a significant increase in the mass flow rate of air and decrease in applied air pressure is often observed. When conducting pneumatic permeability tests in soils having a high moisture content, it is recommended that in-situ moisture monitoring (e.g., neutron probe) be used to determine whether moisture redistribution is occurring.

Derivation of analytical solutions requires additional assumptions

$$\frac{\partial k_r}{\partial r}=0 \quad \frac{\partial k_z}{\partial z}=0 \quad \frac{\partial T}{\partial z}=0 \quad \frac{\partial \mu}{\partial z}=0$$

which state that there is no spatial variation of radial and vertical permeability and that temperature and viscosity do not vary with depth. This allows expression of the air flow equation in a compact form:

$$\frac{\mu\theta}{\sqrt{\phi}}\frac{\partial \phi}{\partial t}=\nabla \bullet (k\nabla\phi) \tag{A.17}$$

This equation, however, is nonlinear, thus some form of linearization of the $\sqrt{\phi}$ term is necessary for analytical analysis. The $\sqrt{\phi}$ term in the denominator on the left hand side of the equation can be handled in at least three different ways. The first and easiest way is to let $\sqrt{\phi}$ equal to a constant. Baehr and Hult (1991) and Falta (1996) explicitly let $\sqrt{\phi} = P_{atm}$. Falta (1996) states that with this approximation, the gas is assumed to be compressible with a constant compressibility factor of $1/P_{atm}$. According to Massmann (1989), for a pressure differential of less than 0.5 atmospheres, this linearization results in an error within a few percent of exact solutions. A second approach is to replace $\sqrt{\phi}$ with a prescribed time-varying function which in some manner reflects the rate of change of the initial pressure distribution (Drake 1997). Drake (1997) attempted linearization through the method of perturbation or successive approximations where each step involves the solution of a linear system. He concluded, however, that at least in his efforts, this approach had not been useful. Johnson, Kemblowski, and Colthart let $P^2 = P \bullet P_{atm}$ and the P term in the denominator of the left hand side of the equation equal to P_{atm}. With the exception of Johnson, Kemblowski, and Colthart's (1988) solution, all analytical solutions given in this paper involved linearization by letting $\sqrt{\phi} = P_{atm}$. With the use of appropriate boundary conditions, Equation A.17 can then be used to develop analytical solutions for air flow in one-dimensional, radial and cylindrical domains.

One-Dimensional, Transient Flow Testing

On a field-scale, one-dimensional, transient flow testing is useful in determining in situ vertical pneumatic permeability due to variation in barometric pressure. The method is based upon the observation that when atmospheric pressure changes at the land surface, air moves to or from the vadose zone to maintain a pressure balance between air in the soil and the atmosphere. The rate of air movement and the resultant rate of pressure change at depth are affected by both the pneumatic permeability and air-filled porosity of materials in the vadose zone (Weeks 1978). Movement of air to and from the vadose zone due to variation in barometric pressure was first analyzed by Buckingham (1904). He presented an equation for the attenuation of the amplitude and phase lag of a periodic atmospheric pressure wave at any depth in a homogeneous layer bounded below by an impermeable boundary (e.g., water table). Later (much later), Stallman (1967) and Stallman and Weeks (1969) measured variation in barometric pressure and pressure variation at depth to determine in situ vertical pneumatic permeability. Their method was based on the assumption that the unsaturated materials comprised a single homogeneous layer. Using the same assumptions, Rosza, Shoeberger, and Baker (1975) used an analytical solution and the principle of superposition to determine pneumatic permeability of material comprising several nuclear chimneys (vertical sections of bedrock containing rubble caused by subsurface nuclear explosions) at the Nevada Test Site. The nuclear chimney rubble was assumed to consist of a homogeneous unit extending to infinity below land surface. Although the assumption that air movement can occur to infinite depth did not accurately represent actual boundary conditions, computed pneumatic permeabilities compared well with those determined by numerical analysis of air injection data. Weeks (1978) used the methods of Stallman (1967) and Stallman and Weeks (1969) to estimate the pneumatic permeability of discrete layers using a numerical one-dimensional program, AIRK. The pneumatic permeability of each layer was determined through trial and error. Air compressibility was ignored, assuming that it would result in insignificant error due to the relatively small magnitude of barometric pressure variations.

Weeks (1978) found it convenient to obtain pressure data during a normal afternoon barometric decline which was equivalent to a pressure drop of 3 to 4 millbars in 4 to 5 hours. Data was collected at 15 minute intervals. Reading continued until 6 or 7 p.m. when a diurnal barometric rise normally occurs. "Chasing fronts" should be resisted as major atmospheric pressure changes occur in a few minutes to an hour and are difficult predict. Weeks (1978) found that pneumatic pressure differences occurring during the normal afternoon diurnal barometric change were large enough to be detected and analyzed at sites where the unsaturated zone was more than 20 meters thick and there was at least one layer with a permeability of no more than 2 to 3 darcies. At other sites, where the unsaturated zone was thinner and the layers more permeable, pressure differences during diurnal change were too small to be accurately measured. Also, short-term atmospheric pressure changes tended to mask longer term trends.

Shan (1995) used a solution containing time-dependent boundary conditions from Carslaw and Jaeger's (1959) classic text on "Conduction of Heat in Solids" to develop a strategy for one-dimensional, transient, pneumatic permeability testing. The governing equation is given as:

$$\frac{\mu\theta}{\sqrt{\phi}}\frac{\partial\phi}{\partial t} = k_z \frac{\partial^2\phi}{\partial z^2} \tag{A.18}$$

Two scenarios for testing are presented: (1) a domain consisting of a region between the water table and the soil surface or at some depth in soil, and (2) a domain between any two points within the soil. The latter scenario provides a method to evaluate pneumatic permeability in discrete layers. Both methods require a minimum of three measurement points; one on each boundary and one between boundaries. For the case of a single layer soil bounded below by the groundwater table, he sets the origin (z=0) at the water table and time variation of pressure at some distance (L) above the water table. Thus the initial and boundary conditions are:

$$\phi(z,0) = f(z) \quad \left.\frac{\partial\phi}{\partial z}\right|_{z=0} = 0 \quad \phi(L,t) = f(t)$$

The solution is given as:

$$I_u = \int_0^L f(z^*)\sin(a_n z^*)dz$$
$$I_w = \int_0^t \exp(a_n^2 \alpha t^*)[f_1(t^*)dt - (-1)^n f_2(t^*)]dt^* \tag{A.19}$$
$$a_n = \frac{(2n+1)\pi}{2L} \quad \alpha = \frac{kP_a}{\theta\mu}$$

where:

$$I_u = \int_0^L f(z^*)\cos(a_n z^*)dz \quad I_w = \int_0^t \exp(a_n^2 \alpha t^*) f(t^*)dt^*$$
$$a_n = \frac{(2n+1)\pi}{2L} \quad \alpha = \frac{kP_a}{\theta\mu}$$

P_a is the mean pressure during testing, and z* and t* are integral variables. These integral variables could have been expressed as any letter but are expressed here with the original variable and an asterisk to remind us that we are solving for z and t. The initial and boundary conditions for the second scenario are:

$$(z,0) \ \ f(z) \qquad (0,t) \ \ f_1(t) \qquad (0,t) \ \ f_2(t)$$

The solution is given as:

$$\phi(z,t) = \frac{2}{L}\sum_{n=0}^{\infty} \exp(-a_n^2 \alpha t)\sin(a_n^2 z)[I_u + \alpha a_n I_w] \tag{A.20}$$

where:

$$I_u = \int_0^L f(z^*)\sin(a_n z^*)dz$$
$$I_w = \int_0^t \exp(a_n^2 \alpha t^*)[f_1(t^*)dt - (-1)^n f_2(t^*)]dt^*$$
$$a_n = \frac{(2n+1)\pi}{2L} \quad \alpha = \frac{kP_a}{\theta\mu}$$

Integration of functions f (z) and f (t) achieved by the use of tabulated data and linear interpolation. This approximation allows piecewise integration of I_u and I_w. Results from 2 test sites are given (27.5 m and 26.5 m). Comparison of simulated versus actual data is generally excellent.

One-Dimensional Steady-State Flow

One-dimensional, steady-state flow is typically used in laboratory column studies and is described by:

$$\frac{d^2\phi}{dz^2} = 0 \tag{A.21}$$

The boundary conditions used to solve this equation are:

$$\phi(z = 0) = \phi_0 \text{ or } \phi_{atm} \qquad \left.\frac{d\phi}{dz}\right|_{z=L} = \frac{-2Q_m RT\mu}{\omega A k_z}$$

The solution to the one-dimensional, steady-state flow equations with these boundary conditions is easily obtained through integration:

$$\phi(z) = \phi_0 - \left(\frac{2Q_m RT\mu}{Ak_z\omega}\right)z \tag{A.22}$$

where A is the cross-sectional area of the column and Q_m is the mass flow rate. In the literature, flow rates are sometimes expressed in terms of volume and sometime in terms of mass. The mixing of units often causes confusion among practitioners. In this Appendix, all flow units are expressed in terms of mass to maintain consistency and to emphasize the point that all analytical solutions given here demand a constant mass flux of air into or out of the formation or column.

The relationship between volumetric flow (Q_v) and mass flow is given by:

$$Q_v = \frac{Q_m RT}{P\omega} \tag{A.23}$$

Radial, Transient, Confined Flow

Without doubt, the equations used most by practitioners in the subsurface remediation field are solutions to the transient and "steady-state" radial flow equation. The transient, radial flow equation is expressed as:

$$\frac{\mu\theta}{\sqrt{\phi}}\frac{\partial\phi}{\partial t} = k_r\left(\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r}\right) \tag{A.24}$$

with boundary conditions:

$$\lim(r \rightarrow \infty)\phi(r,z,t) = \phi_{atm} \qquad r\lim_{r\rightarrow 0}\frac{\partial\phi}{\partial r} = \frac{-Q_m RT\mu}{\pi k_r b\omega}$$

The solution given by Johnson et al. (1988, 1990) is:

$$P' = \frac{Q_m RT\mu}{4\pi P_w \omega bk}\int_u^\infty \frac{e^{-\tau}}{\tau}d\tau \tag{A.25}$$

where:

$$u = \frac{r^2\theta\mu}{4kP_{atm}t}$$

P′ is a gauge pressure. The solution is obtained in P instead of P^2 because Johnson et al. (1988, 1990) linearized the radial, transient equation by letting $P^2 = P^*P_{atm}$ instead of explicitly solving for P^2. A solution to transient, radial flow equation using these boundary conditions, Laplace Transforms and the assumption that $\sqrt{\phi} = P_{atm}$ gives:

$$\phi(r,t) = \phi_{atm} + \frac{Q_m RT\mu}{2\pi bk_r\omega}\int_u^\infty \frac{e^{-\tau}}{\tau}d\tau \tag{A.26}$$

where:

$$u = \frac{\theta\mu r^2}{4k_r tP_{atm}}$$

The integral on the right-hand-side of the equation is the well known exponential integral. When u < 0.01, it can be approximated by:

$$\int_u^\infty \frac{e^{-\tau}}{\tau} d\tau \approx -0.57721 - \ln\ u \tag{A.27}$$

Radial, Pseudo-Steady-State, Confined Flow

The equation describing radial, *pseudo*-steady-state, confined flow is expressed as:

$$\frac{d^2\phi}{dr^2} + \frac{1}{r}\frac{d\phi}{dr} = 0 \tag{A.28}$$

with boundary conditions:

$$\phi(r = r_1) = \phi_1 \qquad r\left.\frac{d\phi}{dr}\right|_{r=r_w} = \frac{-Q_m RT\mu}{\omega\pi b k_r}$$

If air is extracted from soil, Q_m is negative and the solution for the *pseudo*-steady-state flow equation is given by:

$$\phi(r) = \phi_1 + \frac{Q_m RT\mu}{\omega\pi b k_r} \ln\left(\frac{r}{r_1}\right) \tag{A.29}$$

which is a modified form of the well known Thiem Equation. The term *pseudo* steady-state is emphasized because in reality there is no steady-state solution to the radial flow equation unless a constant head boundary is encountered at some radial distance. Otherwise, vacuum or pressure will propagate indefinitely. Inserting ∞ for r in the equation above or $\phi(\infty)$ results in infinite pressure squared at infinite distance, which obviously is not realistic. Johnson et al. (1990) used this equation by letting $\phi(r) = \phi_w$, $\phi_1 = \phi_{atm}$, $r = r_w$, and $r_1 = r_I$ where r_I is "radius of influence" (ROI). In Johnson et al.'s (1990) equation, b is the length of screened interval as opposed to the thickness of the domain as commonly expressed in groundwater hydrology and as expressed in the rest of this Appendix. The ROI is often determined by measuring the radius at which some small subjectively determined vacuum extends from an air extraction well or by extrapolating measurements to zero by transforming radial distance on a logarithmic scale. As can been seen, however, from the general form of the equation, the use of a ROI is unnecessary. One simply needs a vacuum or pressure measurement at two points or at the well and another point. This simple observation is unfortunately missed by many practitioners, since the vacuum measurements in vapor probes around extraction wells are typically used for ROI extrapolation instead of direct pneumatic permeability measurement. Perhaps more importantly though, strictly radial flow rarely occurs in soils during pneumatic permeability testing because of partial penetration of the screened interval and a constant pressure (atmospheric) boundary at the soil surface. Even when a lower permeability lens separates the modeled domain from the atmosphere, there is almost always a strong vertical component of flow because of significant leakage. Soil venting practitioners typically use this equation to estimate pneumatic permeability regardless of applicable boundary conditions. The use of the radial transient, and *pseudo*-steady-state equations are strongly discouraged in favor of solutions derived from cylindrical coordinates which provide more realistic boundary conditions. It is argued by some that “reasonable” results are obtained with radial flow equations even though the boundary conditions are grossly violated. While not as notorious as numerical methods for giving non-unique estimates of permeability, it should be remembered that analytical solutions also can provide incorrect answers while still appearing to “reasonably” fit field data.

Axisymmetric, Cylindrical, Transient, Unconfined, Flow

The previous discussion on the limitations of radial flow modeling provides an introduction on the need to consider the use of axisymmetric, cylindrical equations for determination of pneumatic permeability. The governing equation for unconfined (open to the atmosphere), transient cylindrical flow is:

$$\frac{\mu_a \phi_a}{\sqrt{\phi}} \frac{\partial \phi}{\partial t} = k_r \left(\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} \right) + k_z \frac{\partial^2 \phi}{\partial z^2} \qquad \text{(A.30)}$$

with the initial condition:

$$\phi(r,z,0) = \phi_{atm}$$

and boundary conditions:

$$\phi(r,0,t) = \phi_{atm} \qquad \lim(r \to \infty)\phi(r,z,t) = \phi_{atm} \qquad \left. \frac{\partial \phi}{\partial z} \right|_{z=b} = 0$$

$$\lim(r \to 0) r \frac{\partial \phi}{\partial r} = 0 \qquad l < z < b$$

$$\lim(r \to 0) r \frac{\partial \phi}{\partial r} = 0 \qquad 0 < z < d$$

$$\lim(r \to 0) r \frac{\partial \phi}{\partial r} = -\frac{Q_m RT\mu}{\pi k_r r_w \omega (l-d)} \qquad d < z < l$$

As the boundary conditions indicate, the well is represented as a line source or sink. Falta (1993) provides a solution to axisymmetric, cylindrical, transient, unconfined flow with these stated initial and boundary. The solution is given by:

$$\phi = \phi_{atm} - \frac{Q_m \mu RT}{\pi^2 k_r (l-d)\omega} \sum_{n=1}^{\infty} \left\{ \frac{1}{m} \left[\cos\frac{m\pi d}{b} - \cos\frac{m\pi l}{b} \right] \sin\frac{m\pi z}{b} W(u,\beta_2) \right\}$$

$$m = n - 1/2$$

$$u = \frac{r^2(\theta / P_{atm})}{4(k_r / \mu)t}$$

$$\beta = r\left[\frac{k_z}{k_r} \left(\frac{m\pi}{b} \right)^2 \right]^{1/2}$$

$$W(u,\beta_2) = \int_u^{\infty} \frac{1}{y} \exp\left(-y - \frac{\beta^2}{4y} \right) dy \qquad \text{(A.31)}$$

Axisymmetric, Cylindrical, Steady-State, Unconfined Flow

The governing equation for unconfined (open to the atmosphere), steady-state cylindrical flow is:

$$k_r\left(\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}\right)+k_z\frac{\partial^2\phi}{\partial z^2}=0 \tag{A.32}$$

The boundary conditions are:

$$\phi(r,0,t)=\phi_{atm} \quad \lim(r\rightarrow\infty)\phi(r,z,t)=\phi_{atm} \quad \left.\frac{\partial\phi}{\partial z}\right|_{z=b}=0$$

$$\frac{\partial\phi}{\partial r}=0 \text{ at } r=r_w \quad l<z<b$$

$$\frac{\partial\phi}{\partial r}=0 \text{ at } r=r_w \quad 0<z<d$$

$$\frac{\partial\phi}{\partial r}=-\frac{Q_m RT\mu_a}{\pi K_r r_w \omega(l-d)}$$

Baehr and Hult (1992) provide a solution for unconfined (open to the atmosphere), steady-state cylindrical flow:

$$\phi(r,z)=\phi_{atm}+\frac{2aQ_m\mu RT}{\omega\pi^2 k_r(l-d)r_w}\left\{\sum_{n=1}^{\infty}\alpha_m\sin(M_m z)K_0(M_m r/a)\right\}$$

where:

$$m=n-1/2,\ M_m=m\pi/b,\ a=\left(k_r/k_z\right)^{1/2}, \text{ and}$$

$$\alpha_m=\frac{\cos\left(M_m d\right)-\cos\left(M_m l\right)}{mM_m K_1(M_m r_w/a)} \tag{A.33}$$

Axisymmetric, Cylindrical Transient, Leaky-Confined Flow

Baehr and Hult (1988) adapted Hantush's solution for two-dimensional, axisymmetric, groundwater flow to a partially penetrating well in a leaky-confined aquifer to evaluate air flow in the unsaturated zone induced by a vapor extraction well. Their solution to the air flow equation requires the extraction or injection well to be modeled as an infinitesimal line source and the domain to be bounded above by layer of low permeability. They give the governing equation for leaky-confined, transient, cylindrical flow as:

$$\frac{\mu_a\theta_a}{\sqrt{\phi}}\frac{\partial\phi}{\partial t}=k_r\left(\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}\right)+k_z\frac{\partial^2\phi}{\partial z^2}+\frac{k'}{b'b}(\phi_{atm}-\phi)\qquad\text{(A.34)}$$

with boundary conditions:

$$\lim(r\to\infty)\phi(r,z,t)=\phi_{atm}\qquad\left.\frac{\partial\phi}{\partial z}\right|_{z=b}=0\qquad\left.\frac{\partial\phi}{\partial z}\right|_{z=0}=0$$

$$\lim(r\to 0)r\frac{\partial\phi}{\partial r}=0\ \text{ at }\ r=r_w\ \ 1<z<b$$

$$\lim(r\to 0)r\frac{\partial\phi}{\partial r}=0\ \text{ at }\ r=r_w\ \ 0<z<d$$

$$\lim(r\to 0)r\frac{\partial\phi}{\partial r}=-\frac{Q_mRT\mu}{\pi k_r r_w\omega(1-d)}\quad d<z<1$$

Baehr and Hult's (1989) solution to this equation with given initial, and boundary conditions is:

$$\phi=\phi_{atm}-\frac{Q_m\mu RT}{2\pi k_r b\omega}W(u,\beta_1)-\frac{Q_m\mu RT}{\pi^2 k_r(1-d)\omega}\sum_{n=1}^{\infty}\left\{\frac{1}{n}\left[\sin\frac{n\pi l}{b}-\sin\frac{n\pi d}{b}\right]\cos\frac{n\pi z}{b}W(u,\beta_2)\right\}$$

$$m=n-1/2$$

$$u=\frac{r^2(\theta/P_{atm})}{4(k_r/\mu)t}$$

$$\beta_1=r\left[\frac{k'}{K_r bb'}\right]^{1/2}$$

$$\beta_2=r\left[\frac{k_z}{k_r}\left(\frac{n\pi}{b}\right)^2+\frac{k'}{K_r bb'}\right]^{1/2}$$

$$W(u,\beta_i) = \int_u^\infty \frac{1}{y}\exp\left(-y - \frac{\beta^2}{4y}\right)dy$$
$$i = 1,2 \qquad (A.35)$$

Axisymmetric, Cylindrical, Steady-State, Leaky-Confined Flow

The equation for cylindrical, leaky, leaky-confined, steady-state flow is:

$$k_r\left(\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r}\right) + k_z\frac{\partial^2\phi}{\partial z^2} = 0 \qquad (A.36)$$

with boundary conditions:

$$\lim(r \rightarrow \infty)\phi(r,z) = \phi_{atm}$$

$$\frac{\partial\phi}{\partial r} = 0 \;\text{ at }\; r = r_w \;\; 1 < z < b$$
$$\frac{\partial\phi}{\partial r} = 0 \;\text{ at }\; r = r_w \;\; 0 < z < d$$
$$\frac{\partial\phi}{\partial r} = -\frac{Q_m RT\mu}{\pi K_r r_w \omega(l - d)}$$

$$\left.\frac{\partial\phi}{\partial r}\right|_{z=b} = 0 \qquad k_z\frac{\partial\phi(r,0)}{\partial z} = \frac{k'}{b'}(\phi - \phi_{atm})$$

Here Baehr and Joss (1995) incorporate the leakance term in the boundary conditions as opposed to adding a leakance term in the governing partial differential equation as previously done by Baehr and Hult (1992). Baehr and Joss (1995) state that this boundary condition is an approximation of the conservation of mass principle. It is obtained by using a finite-difference approximation of specific discharge across the thickness of the layer of lower permeability and equating the resultant expression to the vertical component of mass flow defined in the domain as z approaches zero. Baehr and Joss (1995) state that this is a more rigorous approach than adding a leakance term to the governing partial differential equation. Unfortunately, they did not provide an analysis of error incurred by using the stated less rigorous approach.

The solution provided by Baehr and Joss (1995) for axisymmetric, cylindrical, steady-state, leaky confined flow is given by:

$$\phi = \phi_{atm} + \frac{2abhQ_m\mu RT}{\pi k_r \omega(1-d)r_w}\left\{\sum_{n=1}^{\infty}\alpha_n \cos(q_n[b-z]/b)K_0\left(\frac{q_n}{ab}\right)\right\}$$

where:

$$h = (k'b)/(k_z b')$$

$$a = \left(k_r / k_z\right)^{1/2}$$

$$\alpha_n = \frac{\sin\left[q_n(b-d)/b\right]-\sin\left[q_n(b-1)/b\right]}{q_n^2 K_1\left(q_n r_w / ab\right)(h+\sin^2 q_n)}, \text{ and}$$

q_n are positive solutions $(n = 1,2,3,\ldots)$ to

$$\tan(q_n) = h / q_n \tag{A.37}$$

It is important to note that none of the equations for transient testing given here consider the effects of a finite radius well with wellbore storage. Ravi and DiGiulio (1997), however, recently considered these effects for cylindrical transient flow open to the atmosphere, cylindrical, transient flow in a domain separated from the atmosphere by a leaky confining unit, and for radial, transient flow in a perfectly confined system.

For easy reference, Figure A.1 illustrates the variables used in the governing equations for cylindrical coordinates. Tables A.1 and A.2 contain the boundary conditions for all radial and cylindrical coordinates.

Figure A.1
Variables Used in Governing Equations for Vapor Extraction Water Table or an Impervious Unit

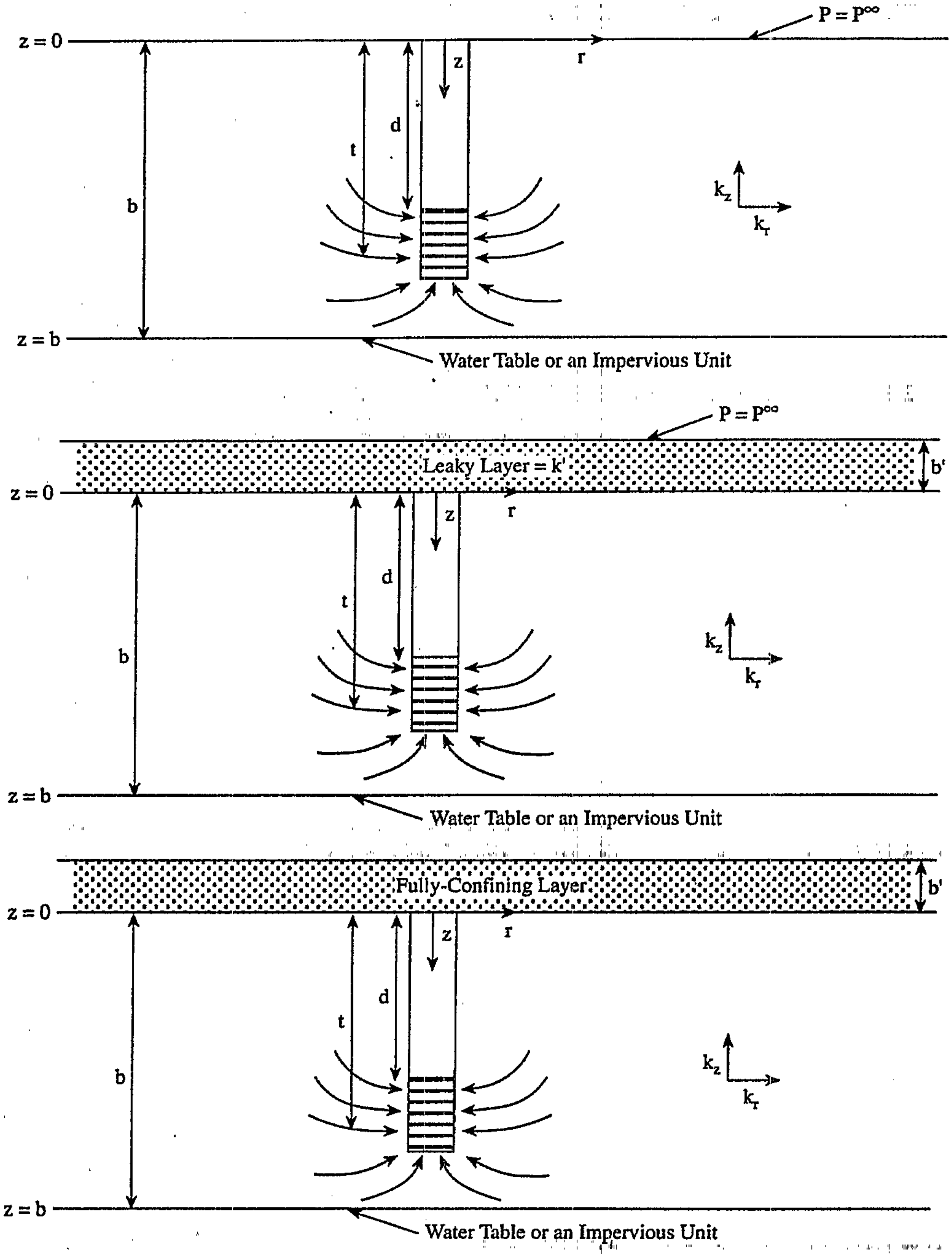

Table A.1
Boundary Conditions for Governing Partial Differential Equations

	Inner	Outer (r > rw)	Upper (z = 0)	Lower (z = b)
One-Dimensional				
Steady-State	NA	NA	a	b
Radial				
Pseudo-Steady-State	d	c	k*	j*
Transient	f	e	k*	j*
Cylindrical-Unconfined				
Steady-State	g	e	a	j
Transient	h	e	a	j
Cylindrical-Leaky Confined				
Steady-State	g	e	i	j
Transient	h	e	k	j

*These boundary conditions are not necessary to solve equations, but are assumed present in radial flow problems.

CONCLUSION

The analytical equations used for pneumatic permeability testing have been derived from basic principles of fluid mechanics. During this derivation process, all the assumptions necessary for analytical model development were identified and most were discussed. The primary assumptions used during pneumatic permeability testing are:

- Darcy's Law is valid for air flow;
- Klinkenberg effect is negligible;
- velocity and gravitational head is negligible;
- ideal gas law correctly defines air density;
- alignment of permeability tensor is in principal direction of vertical and radial permeability;
- temperature gradients in vertical and radial direction are negligible;

Table A.2
Definition of Boundary Conditions

a: $\phi(z=0)=\phi_0 \text{ or } \phi_{atm}$

b: $\left.\frac{d\phi}{dz}\right|_{z=L}=\frac{-2Q_mRT\mu_a}{\omega Ak_z}$

c: $\phi(r=r_l)=\phi_l$

d: $\left.\frac{d\phi}{dr}\right|_{r=r_w}=\frac{-Q_mRT\mu_a}{\omega\pi r_wbk_r}$

e: $\lim_{r\to\infty}\phi(r,z)=\phi_{atm}$

f: $r\lim_{r\to 0}\frac{\partial\phi}{\partial r}=\frac{-Q_mRT\mu_a}{\pi k_rb\omega}$

g:
$$\frac{\partial\phi}{\partial r}=0 \text{ at } r=r_w \quad l<z<b$$
$$\frac{\partial\phi}{\partial r}=0 \text{ at } r=r_w \quad 0<z<d$$
$$\frac{\partial\phi}{\partial r}=-\frac{Q_mRT\mu_a}{\pi K_rr_w\omega(l-d)}$$

h:
$$\lim(r\to 0)r\frac{\partial\phi}{\partial r}=0 \text{ at } r=r_w \quad l<z<b$$
$$\lim(r\to 0)r\frac{\partial\phi}{\partial r}=0 \text{ at } r=r_w \quad 0<z<d$$
$$\lim(r\to 0)r\frac{\partial\phi}{\partial r}=-\frac{Q_mRT\mu_a}{\pi K_rr_w\omega(l-d)} \quad d<z<1$$

i: $k_z\frac{\partial\phi(r,0)}{\partial z}=\frac{k'}{b'}(\phi-\phi_{atm})$

j: $\left.\frac{\partial\phi}{\partial z}\right|_{z=b}=0$

k: $\left.\frac{\partial\phi}{\partial z}\right|_{z=0}=0$

- volumetric water and air contents do not change in space or time;
- air viscosity does not change in space or time;
- vertical and radial permeabilities are constant in space in the simulated domain;
- the air flow equation can be linearized by letting $P_2 = \phi$ and $\sqrt{\phi} = P_{atm}$; and
- capillary fringe no flow boundary remains flat (no upwelling).

Most of these assumptions are reasonable, however, several stand out as being primary causes of error. These are: alignment of permeability tensor in principal direction vertical and radial permeability (anisotropy), constant radial and vertical permeabilities in space, constant volumetric water and air content in time and space, and constant flat lower no flow boundary. Numerical modeling can be used to simulate these effects, however, the problem of nonuniqueness in parameter determination limits the usefulness of this approach. Given these problems, it is wise for the field practitioner to attempt to conduct pneumatic permeability testing in a manner which minimizes deviation from these assumptions, such as low pressure gradient testing in soils having a high water content and to view results in the context of the limitations of analytical modeling.

Analytical solutions from various authors have been summarized. With the exception of solutions developed by Johnson, Kemblowski, and Colthart (1988) and Johnson et al. (1990), all transient solutions employ the linearization of $P^2 = \phi$ and assumption that $\sqrt{\phi} = P_{atm}$. Air flow was expressed in terms of mass versus volume to ensure consistency in the variables used in the equations and to emphasize that for radial and cylindrical coordinate solutions, that constant mass flux is necessary for testing.

B

PROCESS SAFETY REVIEW FOR VE/AS SYSTEMS

This appendix has been adapted from US ACE (1995).

a. *Process Safety Review/HAZOP Review.* A formal hazard and operability (HAZOP) review of the system and its integration with other systems (designed and supplied by others) may be required. The review shall consider operation of each unit, possible hazards, and operation and maintenance difficulties that might occur. All findings shall be recorded, and a formal response shall be prepared. The review should be held no later than 30 calendar days before the start of the vapor extraction/ bioventing system operation, and all deficiencies should be corrected prior to system startup.

b. *HAZOP Study.* A HAZOP study is a formal, systematic, and detailed examination of the process and engineering intent of new or existing facilities to assess the hazard potential of operation outside the design intent or malfunction of individual equipment items and the consequential effects on the facility as a whole.

c. *Guide Words.* During examination sessions, the study team tries to visualize all possible deviations from every design and operating intent. These deviations can each be associated with a word or phrase, called "guide words." When used in association with a design and operating intent, such words guide and stimulate creative thinking toward appropriate deviations. The following is a list of example deviations and associated guide words:

NO FLOW: Wrong routing - blockage - incorrect slip blind - incorrectly installed check valve - burst pipe - large leak - equipment failure (control valve, isolation valve, pump, vessel, etc.) - incorrect pressure differential - isolation in error.

REVERSE FLOW: Defective check valve - siphon effective - incorrect differential pressure - two-way flow - emergency venting - incorrect operation - in-line spare equipment.

American Petroleum Institute (API)

RP500A	Recommended Practice for Classification of Areas for Electrical Installations in Petroleum Refineries
RP500B	Recommended Practice for Classification of Areas for Electrical Installations at Drilling Rigs and Production Facilities on Land and on Fixed and Marine Platforms
RP500C	Electrical Installations at Petroleum and Gas Pipeline Transportation Facilities

American National Standards Institute (ANSI)

C80.1	National Electrical Safety Code Specification for Rigid Steel Conduit, Zinc Coated
C80.5	Specifications for Rigid Aluminum Conduit

National Fire Protection Association (NFPA)

30	Flammable and Combustible Liquids Code
70	National Electrical Code
496	Purged and Pressurized Enclosures for Electrical Equipment in Hazardous Locations
497	Class I Hazardous Locations for Electrical Installations in Chemical Plants

Institute of Electrical and Electronics Engineers (IEEE)

141	Recommended Practice for Electrical Power Distribution for Industrial Plants
518	The Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

C

PROPERTIES OF COMMON ORGANIC POLLUTANTS

This appendix has been adapted from US ACE (1995).

C.1 Introduction

Appendix C consists of 13 tables, each presenting physical and/or chemical properties of compounds and fuel products. This information, including, for example, molecular weights, boiling points, Henry's Law Constants, vapor pressures, and vapor densities may prove helpful in evaluating whether a given site with its contaminants of concern is amenable to Soil Vapor Extraction/Bioventing. In addition, this information may be needed in calculating various operating parameters or outcomes of an Soil Vapor Extraction/Bioventing system at a given site with a given suite of contaminants of concern.

C.2 List of Tables

C.3 *Physicochemical Properties of TCA and Associated Compounds.* Lists same properties as Table C.2 for 1,1,1-TCA; 1,1-DCA; and CA.

C.4 *Physical Properties of Fuel Components.* Lists molecular weight, solubility, soil sorption coefficient, log octanol-water cofficient, and vapor pressure for n-alkanes, isoalkanes, cycloalkanes, alkenes, aromatics, and PAHs.

C.5 *Selected Specification Properties of Aviation Gas Turbine Fuels.* Lists data on composition, volatility, fluidity and combustion for Jet Fuels A and B and JP-4, -5, -7, and -8.

C.6 *Detectable Hydrocarbons Found in U.S. Finished Gasolines at a Concentration of 1% or More.* Lists constituents and estimated ranges of weight percentages of each.

C.7 *Major Component Streams of European Automotive Diesel Oil (Diesel Fuel No. 2) and Distillate Marine Diesel Fuel (Diesel Fuel No. 4).* Lists nonspecific components by Toxic Substances Control Act (TSCA) inventory name and identification number, as well as volumetric percentages of each in both automative diesel oil and distillate marine diesel fuel.

C.8 *Henry's Law Constants for Selected Organic Compounds.* Lists values of H at 20-25°C for chlorinated nonarematics, chlorinated ethers, monocyclic aromatics, pesticides, PCBs, and polycyclic aromatics.

C.9 *Chemical and Physical Properties of TPH Components.* Lists molecular weight, water solubility, specific gravity, vapor pressure, Henry's Law constant, diffusivity, Koc, log Kow, Fish Bioconcentration Factor (BCF), and Surface-Water T1/2, for alcohols, cycloalkenes, cycloalkanes, chlorinated aliphatics, ethers, ketones, methyl alkanes, methyl alkenes, mono- and polycyclic aromatic hydrocarbons, simple alkanes, and simple alkenes.

C.10 *Dimensionless Henry's Law Constants for Typical Organic Compounds.* Lists values of H for various compounds at different temperatures.

C.11 *Chemical Properties of Hydrocarbon Constituents.* Lists liquid density, Henr's Law Constant, water solubility, vapor pressure, vapor density, and Koc for n-alkanes, mono-aromatics, phenols, and diaromatics.

C.12 *Composition of Regular Gasoline.* Lists chemical formula, molecular weight, mass fraction, and mole fraction of 58 components of regular gasoline.

C.13 *Composition of a Weathered Gasoline.* Lists same properties as Table C.12 for 58 components of weathered gasoline.

Table C.1
Selected Compounds and Their Chemical Properties

Compound	M_w (g/mole)	T_b (1 atm) (K)	P_v° (K) (atm)	C_{est} (mg/L)
n-Pentane	72.2	309	0.57	1,700
n-Hexane	86.2	342	0.16	560
Trichloroethane	133.4	348	0.132	720
Benzene	78.1	353	0.10	320
Cyclohexane	84.2	354	0.10	340
Trichloroethylene	131.5	360	0.026	140
n-Heptane	100.2	371	0.046	190
Toluene	92.1	384	0.029	110
Tetrachloroethylene	166	394	0.018	130
n-Octane	114.2	399	0.014	65
Chlorobenzene	113	405	0.012	55
p-Xylene	106.2	411	0.0086	37
Ethylbenzene	106.2	411	0.0092	40
m-Xylene	106.2	412	0.0080	35
o-Xylene	106.2	417	0.0066	29
Styrene	104.1	418	0.0066	28
n-Nonane	128.3	424	0.0042	22.0
n-Propylbenzene	120.2	432	0.0033	16
1,2,4-Trimethylbenzene	120.2	442	0.0019	9.3
n-Decane	142.3	446	0.0013	7.6
Dibromochloropropane	263	469	0.0011	11
n-Undecane	156.3	469	0.0006	3.8
n-Dodecane	170.3	489	0.00015	1.1
Naphthalene	128.2	489	0.00014	0.73
Tetraethyl Lead	323	decomposes @ 473K	0.0002	2.6

M_w	molecular weight
T_b(1 atm)	compound boiling point at 1 atm absolute pressure
P_v° (293 K)	vapor pressure measured at 293 K
C_{est}	equilibrium vapor concentration

Johnson, Kemblowski, and Colthart (1988). "Practical screening models for soil venting applications." In: *Proceedings of NWWA/API; Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater*. Houston, TX. Reprinted by permission of Ground Water Publishing Company ©1988.

Table C.2
Physiochemical Properties of PCE and Associated Compounds*

Formula	PCE/C_2Cl_4	TCE/C_2HCl_3	1,1-DCE/$C_2H_2Cl_2$	t-1,2-DCE/$C_2H_2Cl_2$	c-1,2-DCE/$C_2H_2Cl_2$	VC/C_2H_3Cl
Molecular weight (g/mol)	165.85	131.40	96.95	96.95	96.95	62.5
Liquid density (g/cm^3)	1.625	1.46	1.214	1.257	1.284	0.9121#
Melting point (K)	250.6	200	150.4	223.6	191.5	119.2
Boiling point (K)	394	360	304.6	320.7	333.2	259.6
Vapor pressure (mmHg)	14	69*[1]	500	5.3	2.7	2,300
Water solubility (mg/L)	150	1,100[1]	400	6,300	3,500	1,100
Log octanol - water coefficient	3.14	2.42	2.13	2.09	1.86	1.23
Soil sorption coefficient (L/kg)	665	NA	65	59	35	8.2
Henry's Law constant (atm. m^3/mol)	0.023	.0103[1]	0.154	0.0066[1]	0.0075[1]	0.695

*All values are at 293 K, unless otherwise indicated.
#Value is a specific gravity measurement.
[1] At 298 K.
NA = information not available.

Arthur D. Little, Inc. (1987). *The Installation Restoration Program Toxicology Guide, Volume 1.* Section 2:1-16.

Table C.3
Physiochemical Properties of TCA and Associated Compounds*

Formula	1,1,1-TCA/$C_2H_3Cl_3$	1,1-DCA/$C_2H_4Cl_2$	CA/C_2H_5Cl
Molecular weight (g/mol)	133.42	98.97	64.52
Liquid density (kg/m^3)	1.325	1.175	0.921[1]
Melting point (K)	240	176.3	132.15
Boiling point (K)	347	330.3	285.5
Vapor pressure (mmHg)	100	182	1,000
Water solubility (mg/L)	950	5,500	5,700
Log octanol - water coefficient (L/kg)	2.49	1.79	1.43
Soil sorption coefficient (L/kg)	152	30	14.9
Henry's Law constant (atm. m^3/mol)	0.0276[2]	0.0057[2]	0.011

*All values are at 293 K, unless otherwise indicated.

[1] At 273 K

[2] At 298 K

Arthur D. Little, Inc. (1987). *The Installation Restoration Program Toxicology Guide, Volume 1.* Section 2:1-16.

Table C.4
Physical Properties of Fuel Components

Component	MW	Solubility	K_{oc}	Log K_{ow}	Vapor Pressure
n-Alkanes					
n-Butane	58.12	61			1,555.33
n-Decane	142.28	0.009 (20)			2.7
n-Dodecane	170.33	0.0037	5,500,000	7.06	0.3
n-Hexane	86.18	9.5	3,830	3.9	121.24
n-Heptane	100.20	2.4 (20)			35.55
n-Nonane	128.25	0.07 (20)			3.22
n-Octane	114.23	0.0657	73,000	4.00	10.46
n-Pentane	72.15	38.5			424.38
n-Tridecane	184.35	0.013			
n-Undecane	156.31				1 (32.7)
Isoalkanes					
2-Methyldecane	156.31				
2-Methylhexane	100.20				51.9
2-Methylpentane	86.18	13.8			171.5
2,4-Dimethylhexane	114.23				23.32
2,5-Dimethylhexane	114.23				
2,2,3-Trimethylpentane	114.23		36,000	4.87	
2,2,4-Trimethylpentane	114.23	0.56	36,000	5.02	
3-Methylhexane	100.20				
3-Methylpentane	86.18		3,830	3.9	
3,4-Dimethyloctane	142.28				
4-Methylheptane	114.23				
Isobutane	58.12	48.9			2,252.75
Isododecane	170.33				
Isopentane	72.15	47.7	900	2.3	574.89
Isoundecane	156.31				
Cycloalkanes					
1,3,5-Trimethylcyclohexane	126.24		50,500	5.02	
Cyclohexane	84.16	55.6	1,330	3.44	77.55
Methylcyclohexane	98.19	14 (20)	6,070	4.1	144
Methylcyclopentane	83.15	42.7	1,400	2.35	

Table C.4 (cont.)
Physical Properties of Fuel Components

Component	MW	Solubility	K_{oc}	Log K_{ow}	Vapor Pressure
Alkenes					
Trans-2-Butene	56.11				760 (0.9)
2-Methyl-2-butene	70.13				
Aromatics					
1-Methyl-3-ethylbenzene	120.19				
1-Methyl-3-n-propylbenzene	134.22				
1,2,3-Trimethylbenzene	120.19		2,150	4.65	
1,2,4-Trimethylbenzene	120.19	57.6	2,150	3.65	
1,3,5-Trimethylbenzene	120.19		2,150	3.65	1.73
1,2,3,4-Tetramethylbenzene	134.22				
Benzene	78.11	1,760	65	2.13	75.2
Ethylbenzene	106.17	152	1,200	3.34	7.08
Isopropylbenzene	120.19	50.1		3.43	
Toluene	92.14	515	240	2.69	21.84
Xylenes	106.17	175	700	3.16	6/16
PAHs					
1-Methylnaphthalene	142.20	27	3,570	3.87	
2-Methylnaphthalene	142.20		3,570	3.87	
Acenaphthene	154.21	4.09	5,250	3.98	0.0016 (25)
Acenaphthylene	152.20	3.93	2,890	3.72	0.03
Anthracene	178.23	1.29	13,500	4.45	0.00024 (25)
Chrysene	228.20	0.006	220,000	5.61	6.3E-09 (25)
Naphthalene	128.16	31.7	962	3.3	0.09 (25)
Phenanthrene	178.22	1.24	16,000	4.45	9.4E-04 (25)
Pyrene	202.24	0.15	44,000	4.88	2.5E-06 (25)

Solubility in mg/L water at 198 K, unless otherwise noted in parentheses.
Vapor Pressure of pure compound in mm Hg at 20 °C, unless otherwise noted in parentheses.

ABB Environmental Services, Inc. (1990). "Compilation of data on the composition, physical characteristics and water solubility of fuel products." Prepared for: Massachusetts Department of Environmental Protection. Job No. 6042-04. pp 1-3.

Table C.5
Selected Specification Properties of Aviation Gas Turbine Fuels

Characteristic	Civil ASTM D 1655		Military[a]			
			Mil-T-5624-K		Mil-T-38219	Mil-T-83133
	Jet A kerosene	Jet B wide-cut	JP-4 wide-cut USAF	JP-5 kerosene USN	JP-7[b] kerosene USAF	JP-8 kerosene USAF
Composition						
aromatics, % by volume maximum	20[c]	20[c]	25	25	5	25
sulfur, % by weight maximum	0.3	0.3	0.4	0.4	0.1	0.4
Volatility						
distillation-10% received	204			205	196	205
temperature-50% received		188	190			
maximum k-endpoint	573		543	563	561	573
vapor pressure at 311 K kPa maximum (psi)		21(3)	14-21(2-3)			
density at 288 K, kg/m^3	775-840	751-802	751-802	788-845	779-806	775-840
Fluidity						
freezing-point, k maximum	233[d]	223	215	227	230	223
viscosity at 253 K, mm^3/s maximum (=cSt)	8.0			8.5	8.0	8.0
Combustion						
heat content, MJ/kg, minimum	42.8	42.8	42.8	42.6	43.5	42.8
smoke point, mm, minimum	20[e]	20[e]	20	19	35[b]	20
H_2 content, % by weight minimum			13.6	13.5	14.2[b]	13.6

[a] USAF = US Air Force; USN = US Navy
[b] Estimated properties for advanced supersonic fuel
[c] Fuel up to 25% by volume aromatics may be supplied on notification (22% by volume or Jet A-1, Jet B)
[d] International airlines use Jet A-1 with 223 k freeze-point
[e] Fuel with 18 smoke point may be supplied on notification (19 for Jet A-1, Jet B)

World Health Organization, International Agency for Research on Cancer. (1989). "IARC monographs on the evaluation of carcinogenic risks to humans - occupational exposures in petroleum refining; crude oil and major petroleum fuels." Volume 45. *IARC*, Lyon, France.

Table C.6

Detectable Hydrocarbons Found in U.S. Finished Gasolines at a Concentration of 1% or More[a]

Chemical	Weight %	
	Estimated Range	Weighted Average[b]
Toluene	5-22	10
2-Methylpentane + 4-Methyl-cis-2-pentene + 3-Methyl-cis-2-pentene[c]	4-14	9
n-Butane	3-12	7
iso-Pentane	5-10	7
n-Pentane	1-9	5
Xylene (three isomers)	1-10	3
2,2,4-Trimethylpentane	< 1-8	3
n-Hexane	< 1-6	2
n-Heptane	< 1-5	2
2,3,3-Trimethylpentane	< 1-5	2
2,3,4-Trimethylpentane	< 1-5	2
3-Methylpentane	< 1-5	2
Methylcyclohexane + 1-cis-2-Dimethylcyclopentane + 3-Methylhexane[c]	< 1-5	1
Benzene	< 1-4	2
2,2,3-Trimethylpentane	< 1-4	2
Methyl tertiary butyl ether	< 1-4	1
Methylcyclopentane	< 1-3	2
2,4-Dimethylpentane	< 1-3	1
Cyclohexane	< 1-3	1
1,2,4-Trimethylbenzene	< 1-3	1
2-Methyl-2-butene	< 1-2	2
2,3-Dimethylbutane	< 1-2	1
trans-2-Pentene	< 1-2	1
Methylcyclohexane	< 1-2	1
3-Ethyltoluene	< 1-2	1
2,3-Dimethylpentane	< 1-2	1
2,5-Dimethylpentane	< 1-2	1
2-Methyl-1-butene	< 1-2	1
Ethyl benzene	< 1-2	1

[a] Provided by American Petroleum Institute

[b] The sum of the weighted average does not equal 100% because numerous components were detected at less than 1%.

[c] These chemicals could not be distinguished by gas chromatography because of similar retention times.

World Health Organization, International Agency for Research on Cancer. (1989). "IARC monographs on the evaluation of carcinogenic risks to humans - occupational exposures in petroleum refining; crude oil and major petroleum fuels." Volume 45. *IRAC*, Lyon, France.

Table C.7
Major Component Streams of European Automotive Diesel Oil (Diesel Fuel No. 2) and Distillate Marine Diesel Fuel (Diesel Fuel No. 4)

Toxic Substances Control Act (TSCA) Inventory Name and Identification Number	Refinery Process Stream (nomenclature used in Europe)	Automotive Diesel Oil (% by volume)	Distillate Marine Diesel Fuel (% by volume)
Straight-run (atmospheric) gas oil			
Straight-run middle distillate	light	40-100	0-3
Straight-run gas oil	heavy	40-100	0-50
Light vacuum distillate	Vacuum gas oil	0-10	0-20
Light thermally cracked distillate	Thermally cracked gas oil	0-20	0-30
Light catalytically cracked distillate	Light catalytically cracked gas oil (cycle oil)	0-25	0-40

World Health Organization, International Agency for Research on Cancer. (1989). "IARC monographs on the evaluation of carcinogenic risks to humans - occupational exposures in petroleum refining; crude oil and major petroleum fuels." Volume 45. *IRAC*, Lyon, France.

Table C.8

Henry's Law Constants (H, atm-m^3/mol) for Selected Organic Compounds

Compound	H	t (K)[a]
Chlorinated Nonaromatics		
Benzene	0.0055	298
Chlorobenzene	0.0036	293/298
o-Dichlorobenzene	0.0019	293
m-Dichlorobenzene	0.0036	298
p-Dichlorobenzene	0.0031	298
1,2,4-Trichlorobenzene	0.0023	298
Methyl chloride	0.04	293
Methyl bromide	0.20	293
Methylene chloride	0.0020	293/298
Chloroform	0.0029	293
Bromodichloromethane	0.0024	293/295
Dibromochloromethane	0.00099	293/295
Bromoform	0.00056	293
Dichlorodifluoromethane	3.0	298
Trichlorofluoromethane	0.11	293
Carbon tetrachloride	0.023	293
Chloroethane	0.15	293
1,1-Dichloroethane	0.0043	293
1,2-Dichloroethane	0.00091	293
1,1,1-Trichloroethane	0.03	298
1,1,2-Trichloroethane	0.00074	293
1,1,2,2-Tetrachloroethane	0.00038	293
Hexachloroethane	0.0025	293/295
Vinyl chloride	0.081	298
1,1-Dichloroethene	0.19	298/293
1,2-trans-Dichloroethene	0.067	293
Trichloroethene	0.0091	293
Tetrachloroethene	0.0153	293
1,2-Dichloropropane	0.0023	293
trans-1,3-Dichloropropene	0.0013	293/298
Hexachlorocyclopentadiene	0.016	298
Hexachlorobutadiene	0.026	293
Chlorinated Ethers		
Bis(chloromethyl)ether	0.00021	293/298
Bis(2-chloroisopropyl)ether	0.00011	293
4-Chlorophenylphenylether	0.00022	293
4-Bromophenylphenylether	0.00010	293/298
Monocyclic Aromatics		
Naphthalene	0.00046	298
Acenaphthene	0.000091	298
Acenaphthylene	0.0015	293/298
Anthracene	0.000086	298
Phenanthrene	0.00023	298

Table C.8 (cont.)
Henry's Law Constants (H, atm-m^3/mol) for Selected Organic Compounds

Compound	H	t (K)[a]
Polycyclic Aromatics		
Hexachlorobenzene	0.00068	293/298
Toluene	0.0067	293
Ethylbenzene	0.0066	293
o-Xylene	0.0050	298
m-Xylene	0.0070	298
p-Xylene	0.0071	298
1,2,3-Trimethylbenzene	0.0032	298
1,2,4-Trimethylbenzene	0.0059	298
1,3,5-Trimethylbenzene	0.0060	298
Propylbenzene	0.0070	298
Isopropylbenzene	0.0013	298
1-Ethyl-2-methylbenzene	0.0043	298
1-Ethyl-4-methylbenzene	0.0050	298
n-Butylbenzene	0.013	298
Isobutylbenzene	0.033	298
sec-Butylbenzene	0.014	298
tert-Butylbenzene	0.012	298
1,2,4,5-Tetramethylbenzene	0.025	298
1-Isopropyl-4-methylbenzene	0.0080	298
n-Pentylbenzene	0.0060	298
Pesticide and Related Compounds, and PCBs		
Ethylene dibromide (EDB)	0.00082	298
trans-Chlordane	0.000094	298
Heptachlor	0.0040	298
Heptachlor epoxide	0.00039	298
2,3,7,8-TCDD	0.0021	–
Aroclor 1016[b]	0.00033	298
Aroclor 1221[b]	0.00017	298
Aroclor 1242[b]	0.0020	298
Aroclor 1248[b]	0.0036	298
Aroclor 1254[b]	0.0026	–

[a] Where two temperatures are given, the first is the temperature at which the vapor pressure was measured, and the second is the tempera ture at which the solubility was measured.

[b] Mixture-average value.

Pankow, J.F., Johnson, R.L., and Cherry, J.A. (1993). Air sparging in gate wells in cutoff walls and trenches for control of volatile organics, *Ground Water* 31(4):654-63. Reprinted by permission of Ground Water Publishing Company ©1993.

Table C.9
Chemical and Physical Properties of TPH Components

Constituents	Molecular Weight	Water Solubility mg/L 298 K	Specific Gravity	Vapor Pressure mm Hg 298 K	Henry's Law Constant atm-m^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days) Low-High
Alcohols										
Ethyl alcohol	46.07	280,000	0.789	59	1.2E-05	0.12368	0.3	3.1	0.34	
Methyl alcohol	32	300,000		130	2.0E-05	0.16211	0.1	1.5	2.3	
t-Butyl alcohol	74.1		0.788	42		0.09752		0.37		
Cycloalkanes										
Cyclopentane	70.14	160	0.751	42.4	1.9E+01					
Methyl cyclohexane	98.19	14	0.77	6.18	4.3E+01					
Cycloalkenes										
Cyclohexene	84.16	55 (20°C)	0.779							
Cyclopentene	68.12		0.77	77 (20°C)						
Chlorinated Aliphatics										
1,2-Dichloroethane	99	7,986-8,650	1.23	87	1.3E-03	0.09451	65	1.48-2.13	5.6	28-180
Dibromoethane	187.88	4.32 (30°C)	2.701	17 (30°C)						
1,1-Dichloroethane	99	5,060	1.1757	182.1	5.9E-03	0.0959	30.2	1.79		
Ether										
Methyl-t-butyl ether	88	4,800	0.74	250	5.9E-03	0.10172	41	1.2	1.5	28-180
Ketone										
Methyl isobutyl ketone	100.2	20,400	0.8017	14.5	9.4E-05	0.07588	19 to 106	1.19		

Methyl Alkanes					
2,3-Dimethylbutane	86.7	19.1		31.3	1.3E+02
2,3-Dimethylpentane	100.21	5.25		9.18	1.8E+02
2,4-Dimethylpentane	100.21	5.5		13.1	3.0E+02
3,3-Dimethylpentane	100.21	5.94		11	1.9E+02
2-Methylheptane	114.23				
3-Methylheptane	114.23	0.792		2.6	3.8E+02
4-Methylheptane	114.23				
2-Methylhexane	100.21	2.54		8.78	3.5E+02
3-Methylhexane	100.21	4.95		8.21	2.4E+02
4-Methyloctane	128.26	0.115		0.903	1.0E+03
2-Methylpentane	86.17	13	0.654	28.2	1.7E+02
3-Methylpentane	86.17	13.1	0.6645	25.3	1.7E+02
2,2,4-Trimethylhexane	128.26				
2,2,5-Trimethylhexane	128.26	1.15		2.21	3.5E+02
2,3,3-Trimethylhexane	128.26				
2,3,5-Trimethylhexane	128.26				
2,4,4-Trimethylhexane	128.26				
2,2,3-Trimethylpentane	114.23				
2,2,4-Trimethylpentane	114.23	2.44		6.56	3.3E+02
2,3,3-Trimethylpentane	114.23				
2,3,4-Trimethylpentane	114.23	2.3		3.6	1.9E+02
Methyl Alkenes					
2-Methyl-1-butene	70.14		0.65		
2-Methyl-2-butene	70.14		0.668		

Table C.9 (cont.)
Chemical and Physical Properties of TPH Components

Constituents	Molecular Weight	Water Solubility mg/L 298 K	Specific Gravity	Vapor Pressure mm Hg 298 K	Henry's Law Constant atm-m³/mol 298 K	Diffusivity cm²/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days) Low-High
Methyl Alkenes										
3-Methyl-1-butene	70.14	130	0.648	120	5.5E+01					
2-Methyl-1-pentene	86.16	78	0.6817							
2-Methyl-2-pentene	86.16									
3-Methyl-cis-2-pentene	86.16									
3-Methyl-trans-2-pentene	86.16			0.67						
4-Methyl-cis-2-pentene	86.16			0.67						
4-Methyl-trans-2-pentene	86.16									
Monocyclic Aromatic Hydrocarbons										
Benzene	78	1.780	0.88	95	5.5E-03	9.30E-02	49 to 100	1.56 to 2.15	52	5
Butylbenzene	134		0.86	1 (23°C)			1,500			
n-Butylbenzene	134	50	0.86	1 (23°C)	1.3E+00					
sec-Butylbenzene	134	30.9	0.87	1.5 (20°C)	1.4E+00					
t-Butylbenzene	134	34	0.862	1.1 (20°C)	1.2E+00					
1,2-Diethylbenzene	136						1,500			
1,3-Diethylbenzene	136						1,500			
Ethylbenzene	106	152 to 208	0.87	95	8.7E-03	6.70E-02	95 to 260	3.05 to 3.15	37.5	3

Isobutylbenzene	134.2	10.1		0.248	3.3E+00					
eip-Isopropylbenzene	120	50 (20°C)	0.862	3.2 (20°C)	1.0E-02			3.66		2
n-Pentylbenzene	149						2,520			
Propylbenzene	120.2	60		0.449	7.0E-1					
n-Propylbenzene	120	60 (15C)	0.862	2.5 (20°C)	5.6E-03 (15°C)			3.57 to 3.68		
1,2,3,4-Tetramethylbenzene	215.9	4.31		0.00876	2.6E-01		1,500			
1,2,3,5-Tetramethylbenzene	215.9	3.5		0.0186	5.9E-01		1,500			
1,2,4,5-Tetramethylbenzene	134.2	3.48		0.0659	2.5E+00		1,500			
Toluene	92	490 to 627	0.87	28	6.7E-03	7.80E-02	115 to 150	2.11 to 2.8	10.7	4
1,2,3-Trimethylbenzene	120						884			
1,2,4-Trimethylbenzene	120	57 (20°C)	0.88	1.4	3.9E-01 (20°C)		1,600	3.4	230	7
1,3,5-Trimethylbenzene	120	64	0.865	1.4	3.7E-01	1.60E+02	3.4	230		
m-Xylene	106	173	0.8684	10	6.3E-03		1,585	3.2		
o-Xylene	106	204	0.87596	10	5.4E-03		129	2.77 to 3.16		
p-Xylene	106	200	0.85665	10	6.3E-03		204	3.15		
Xylenes	106	162 to 200	0.87	6.6 to 8.8	6.3E-03	7.20E-02	128 to 1,580	2.77 to 3.2	132	7
Polycyclic Aromatic Hydrocarbons										
Anthracene	178	0.030 to 0.1125	1.24	1.7E-05 to 1.95E-4	6.5E-05	5.90E-02	16,000 to 26,000	4.34 to 4.54	30	0.071/0.024
Benzo(a)pyrene	252	0.0038 to 0.004	1.35	5.5E-09	< 2.4E-6	4.70E-02	398,000 to 1,900,000	5.81 to 6.50	30	0.015/0.046
Benzo(b)fluoranthene	252	0.0012	ND	5.0E-07	1.2E-05	4.40E-02	550,000	6.57	ND	0.36

Table C.9 (cont.)
Chemical and Physical Properties of TPH Components

Constituents	Molecular Weight	Water Solubility mg/L 298 K	Specific Gravity	Vapor Pressure mm Hg 298 K	Henry's Law Constant atm-m^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days) Low-High
Polycyclic Aromatic Hydrocarbons										
Benzo(e)pyrene	252					4.70E-02				
1,2-Dimethylnaphthalene	158						4,230			
1,3-Dimethylnaphthalene	158						4,230			
Fluoranthene	202	0.206 to 0.373	1.25	0.000005	1.7E-02	4.2E-02	5.22	1,150	0.875	2.6
Fluorene	166	1.66 to 1.98	1.2	1E-3 to 1E-2	2.1E-04	5.70E-02	5,000	4.12 to 4.38	30	32
Methylnaphthalene	142	27								
1-Methylnaphthalene	142	28	1.025	ND	ND	ND	ND	ND	129	ND
2-Methylnaphthalene	142	25	1.001	0.045	3.4E-04	6.20E-02	7,400 to 8,500	3.86 to 4.11	190	ND
Naphthalene	128	30 to 34	1.16	2.3E-1 to 8.7E-1	4.6E-04	8.20E-02	550 to 3,160	3.2 to 4.7	10.5	0.5
Phenanthrene	178	0.71 to 1.29	1.18	0.00068	2.6E-05	5.40E-02	5,250 to 38,900	4.2 to 4.6	30	0.125/1.04
Pyrene	202	0.013 to 0.171	1.27	6.85E-07 to 2.5E-06	1.1E-05	5.00E-02	46,000 to 135,000	4.88 to 5.32	30	0.028/0.085

Simple Alkanes										
n-Butane	58.13	61	0.6	1.82E+03	9.6E-01					
Decane	148.28	0.008								
n-Decane	148.28	0.052		1.31	7.0E+00					
Dodecane	170.33	0.0037		0.0118	7.5E+00					
n-Dodecane	170.33									
n-Eicosane	282.6	0.0019		2.67E-06	2.9E-01					
n-Heptane	100.21	3		0.515	2.3E+00					
n-Hexadecane	226.44	0.00628		0.00917	2.3E+01					
n-Hexane	86	18 (20°C)	0.66	1.2E-2 (20°C)	7.7E-01	7.50E-02	890	2.77	ND	ND
Isobutane	58.13	48.19		2,678	1.2E+00					
Isopentane	72.15	48		695	1.4E+00					
n-Nonane	128.26	0.07		4.281	5.0E+00					
n-Octadecane	254.4	0.0021		2.50E-05	2.9E+00					
n-Octane	114.23	0.66		14	3.0E+00					
n-Pentane	72.15	35		513	1.3E+00					
Propane	44.09	63	0.58	64						
n-Tetradecane	190.38	0.00696		0.0095	1.1E+00					
Undecane	156.32	0.044		0.39	1.9E+01					
n-Undecane	156.32									

Table C.9 (cont.)
Chemical and Physical Properties of TPH Components

Constituents	Molecular Weight	Water Solubility mg/L 298 K	Specific Gravity	Vapor Pressure mm Hg 298 K	Henry's Law Constant atm-m^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days) Low-High
Simple Alkenes										
2-Butene		210								
cis-2-Butene	56.1		0.6							
trans-2-Butene	56.1		0.64							
cis-3-Heptene	98	9								
trans-3-Heptene	98									
cis-2-Hexene	84	50	0.86							
trans-2-Hexene	84	50	0.86							
cis-3-Hexene	84									
trans-3-Hexene	84									
1-Pentene	70.14	150		85	4.0E+01					
2-Pentene	70.14	203		66	2.3E+01					
cis-2-Pentene	70.14									
trans-2-Pentene	70.14									

BCF	bioconcentration factor
$T_{1/2}$	half life
ND	not detected

Heath, J.S., Koblis, K., Sager, S.L., and Day, C. (1993). Risk assessment for total petroleum hydrocarbons. Calabrese, E.J., and Kostecki, P.T. (eds.). *Hydrocarbon Contaminated Soils - Volume III*. Lewis Publishers, Chelsea, MI. pp. 267-301. Reprinted by permission of Lewis Publishers, an imprint of CRC Press, Boca Raton, FL.

Table C.10
Dimensionless Henry's Law Constants for Typical Organic Compounds

Component	283 K	289 K	293 K	298 K	303 K
Nonane	17.21519	20.97643	13.80119	16.92131	18.69235
n-Hexane	10.24304	17.46626	36.70619	31.39026	62.70981
2-Methylpentane	29.99747	29.35008	26.31372	33.72000	34.08841
Cyclohexane	4.43291	5.32869	5.81978	7.23447	8.96429
Chlorobenzene	0.10501	0.11884	0.14175	0.14714	0.19014
1,2-Dichlorobenzene	0.07015	0.06048	0.06984	0.06417	0.09527
1,3-Dichlorobenzene	0.09511	0.09769	0.12222	0.11649	0.16964
1,4-Dichlorobenzene	0.09124	0.09177	0.10767	0.12957	0.15637
o-Xylene	0.12266	0.15267	0.19704	0.19905	0.25164
p-Xylene	0.18076	0.20427	0.26813	0.30409	0.37988
m-Xylene	0.17689	0.20976	0.24859	0.30409	0.35656
Propylbenzene	0.24446	0.30915	0.36623	0.44143	0.55072
Ethylbenzene	0.14030	0.19073	0.24983	0.32208	0.42209
Toluene	0.16397	0.20807	0.23071	0.26240	0.32480
Benzene	0.14203	0.16409	0.18790	0.21581	0.28943
Methylethylbenzene	0.15106	0.17762	0.20910	0.22807	0.30953
1,1-Dichloroethane	0.15838	0.19200	0.23404	0.25545	0.31194
1,2-Dichloroethane	0.05035	0.05498	0.06111	0.05763	0.06995
1,1,1-Trichloroethane	0.41532	0.48635	0.60692	0.71119	0.84819
1,1,2-Trichloroethane	0.01678	0.02664	0.03076	0.03719	0.05346
cis-1,2-Dichloroethylene	0.11620	0.13787	0.14965	0.18556	0.23114
trans-1,2-Dichloroethylene	0.25390	0.29815	0.35625	0.38625	0.48640
Tetrachloroethylene	0.36410	0.46943	0.58614	0.69892	0.98487
Trichloroethylene	0.23154	0.28208	0.35002	0.41690	0.51454
Tetralin	0.03228	0.04441	0.05654	0.07643	0.10773
Decalin	3.01266	3.53977	4.40641	4.78211	7.99952
Vinyl chloride	0.64557	0.71049	0.90207	1.08313	1.12556
Chloroethane	0.32666	0.40515	0.45727	0.49456	0.57484
Hexachloroethane	0.25522	0.23641	0.24568	0.34129	0.41405
Carbon tetrachloride	0.63696	0.80776	0.96442	1.20575	1.51951
1,3,5-Trimethylbenzene	0.17344	0.19454	0.23736	0.27507	0.38711
Ethylene dibromide	0.01291	0.02030	0.02536	0.02657	0.03216
1,1-Dichloroethylene	0.66278	0.85851	0.90622	1.05860	1.27832
Methylene chloride	0.06025	0.07147	0.10143	0.12098	0.14512
Chloroform	0.07403	0.09854	0.13801	0.17207	0.22270
1,1,2,2-Tetrachloroethane	0.01420	0.00846	0.03035	0.01022	0.02814
1,2-Dichloropropane	0.05251	0.05329	0.07898	0.14592	0.11497
Dibromochloromethane	0.01635	0.01903	0.04282	0.04823	0.06110
1,2,4-Trichlorobenzene	0.05552	0.04441	0.07607	0.07848	0.11939
2,4-Dimethylphenol	0.35678	0.28504	0.41986	0.20150	0.15074
1,1,2-Trichlorotrifluoroethane	6.62785	9.09260	10.18462	13.03840	12.90375
Methyl ethyl ketone	0.01205	0.01649	0.00790	0.00531	0.00442
Methyl isobutyl ketone	0.02841	0.01565	0.01206	0.01594	0.02734
Methyl cellosolve	1.89798	1.53517	4.82210	1.26297	1.53277
Trichlorofluoromethane	2.30684	2.87580	3.34222	4.12815	4.90423

Source: US EPA

Table C.11
Chemical Properties of Hydrocarbon Constituents

Chemical Class	Representative Chemical	Liquid Density (g/cm^3)@293 K	Henry's Law Constant (dimensionless)	Water Solubility (mg/L)@298 K	Pure Vapor Pressure (mm Hg)@293 K	Vapor Density (g/m^3)@293 K	Soil Sorption Constant (K_{oc}) (L/kg)@298 K
n-Alkanes							
C4	n-Butane	0.579	25.22	61.1	1,560	4,960	250
C5	n-Pentane	0.626	29.77	41.2	424	1,670	320
C6	n-Hexane	0.659	36.61	12.5	121	570	600
C7	n-Heptane	0.684	44.60	2.68	35.6	195	1,300
C8	n-Octane	0.703	52.00	0.66	10.5	65.6	2,600
C9	n-Nonane	0.718	NA	0.122	3.2	22.4	5,800
C10	n-Decane	0.730	NA	0.022	0.95	7.4	13,000
Mono-aromatics							
C6	Benzene	0.885	0.11	1,780	75.2	321	38
C7	Toluene	0.867	0.13	515	21.8	110	90
C8	m-Xylene	0.864	0.12	162	6.16	35.8	220
C8	Ethylbenzene	0.867	0.14	167	7.08	41.1	210
C9	1,3,5-Trimethylbenzene	0.865	0.09	72.6	1.73	11.4	390
C10	1,4-Diethylbenzene	0.862	0.19	15	0.697	5.12	1,100
Phenols							
Phenol	Phenol	1.058	0.038	82,000	0.529	2.72	110
C1-Phenols	m-Cresol	1.027	0.044	23,500	0.15	0.89	8.4
C2-Phenols	2,4-Dimethylphenol	0.965	0.048	1,600	0.058	0.39	NA
C3-Phenols	2,4,6-Trimethylphenol	NA	NA	NA	0.012	0.09	NA
C4-Phenols	m-Ethylphenol	1.037	NA	NA	0.08	0.53	NA
Indanol	Indanol	NA	NA	NA	0.014	0.1	NA
Di-aromatics	Naphthalene	1.025	NA	30	0.053	0.37	690

NA not available

Source: US EPA

Table C.12
Composition of a Regular Gasoline

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial Mass Fraction	Initial Mole Fraction
Propane	C3H8	44.1	0.0001	0.0002
Isobutane	C4H10	58.1	0.0122	0.1999
n-Butane	C4H10	58.1	0.0629	0.1031
trans-2-Butene	C4H10	56.1	0.0007	0.0012
cis-2-Butene	C4H10	56.1	0.0000	0.0000
3-Methyl-1-butene	C5H10	70.1	0.0006	0.0008
Isopentane	C5H12	72.2	0.1049	0.1384
1-Pentene	C5H10	70.1	0.0000	0.0000
2-Methyl-1-butene	C5H10	70.1	0.0000	0.0000
2-Methyl-1,3-butadiene	C5H8	68.1	0.0000	0.0000
n-Pentane	C5H12	72.2	0.0586	0.0773
trans-2-Pentene	C5H10	70.1	0.0000	0.0000
2-Methyl-2-butene	C5H10	70.1	0.0044	0.0060
3-Methyl-1,2-butadiene	C5H8	68.1	0.0000	0.0000
3,3-Dimethyl-1-butene	C6H12	84.2	0.0049	0.0055
Cyclopentane	C5H10	70.1	0.0000	0.0000
3-Methyl-1-pentene	C6H12	84.2	0.0000	0.0000
2,3-Dimethylbutane	C6H14	86.2	0.0730	0.0807
2-Methylpentane	C6H14	86.2	0.0273	0.0302
3-Methylpentane	C6H14	86.2	0.0000	0.0000
n-Hexane	C6H14	86.2	0.0283	0.0313
Methylcyclopentane	C6H12	84.2	0.0000	0.0000
2,2-Dimethylpentane	C7H16	100.2	0.0076	0.0093
Benzene	C6H6	78.1	0.0076	0.0093
Cyclohexane	C6H12	84.2	0.0000	0.0000
2,3-Dimethylpentane	C7H16	100.2	0.0390	0.0371
3-Methylhexane	C7H16	100.2	0.0000	0.0000
3-Ethylpentane	C7H16	100.2	0.0000	0.0000

Table C.12 (cont.)
Composition of a Regular Gasoline

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial	
			Mass Fraction	Mole Fraction
2,2,4-Trimethylpentane	C8H18	114.2	0.0121	0.0101
n-Heptane	C7H16	100.2	0.0063	0.0060
Methylcyclohexane	C7H14	98.2	0.0000	0.0000
2,2-Dimethylhexane	C8H18	114.2	0.0055	0.0046
Toluene	C7H8	92.1	0.0550	0.0568
2,3,4-Trimethylpentane	C8H18	114.2	0.0121	0.0101
2-Methylheptane	C8H18	114.2	0.0155	0.0129
3-Methylheptane	C8H18	114.2	0.0000	0.0000
n-Octane	C8H18	114.2	0.0013	0.0011
2,4,4-Trimethylhexane	C9H20	128.3	0.0087	0.0065
2,2-Dimethylheptane	C9H20	128.3	0.0000	0.0000
p-Xylene	C8H10	106.2	0.0957	0.0858
m-Xylene	C8H10	106.2	0.0000	0.0000
3,3,4-Trimethylhexane	C9H20	128.3	0.0281	0.0209
o-Xylene	C8H10	106.2	0.0000	0.0000
2,2,4-Trimethylheptane	C10H22	142.3	0.0105	0.0070
3,3,5-Trimethylheptane	C10H22	142.3	0.0000	0.0000
n-Propylbenzene	C9H12	120.2	0.0841	0.0666
2,3,4-Trimethylheptane	C10H22	142.3	0.0000	0.0000
1,3,5-Trimethylbenzene	C9H12	120.2	0.0411	0.0325
1,2,4-Trimethylbenzene	C9H12	120.2	0.0213	0.0169
Methylpropylbenzene	C10H14	134.2	0.0351	0.0249
Dimethylethylbenzene	C10H14	134.2	0.0307	0.0218
1,2,4,5-Tetramethylbenzene	C10H14	134.2	0.0133	0.0094
1,2,3,4-Tetramethylbenzene	C10H14	134.2	0.0129	0.0091
1,2,4-Trimethyl-5-ethylbenzene	C11H16	148.2	0.0405	0.0260
n-Dodecane	C12H26	170.3	0.0230	0.0129
Naphthalene	C10H8	128.2	0.0045	0.0033
n-Hexylbenzene	C12H20	162.3	0.0000	0.0000
Methylnaphthalene	C11H10	142.2	0.0023	0.0015
Total			0.9917	1.0000

Johnson, P.C., Kemblowski, M.W., and Colthart, J.D. (1990b). "Quantitative analysis for the cleanup of hydrocarbon-con taminated soils by in-situ venting," *Ground Water* 28(3):413-29.
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Table C.13
Composition of a Weathered Gasoline

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial Mass Fraction	Initial Mole Fraction
Propane	C3H8	44.1	0.0000	0.0000
Isobutane	C4H10	58.1	0.0000	0.0000
n-Butane	C4H10	58.1	0.0000	0.0000
trans-2-Butene	C4H8	56.1	0.0000	0.0000
cis-2-Butene	C4H8	56.1	0.0000	0.0000
3-Methyl-1-butene	C5H10	70.1	0.0000	0.0000
Isopentane	C5H12	72.2	0.0200	0.0290
1-Pentene	C5H10	70.1	0.0000	0.0000
2-Methyl-1-butene	C5H10	70.1	0.0000	0.0000
2-Methyl-1,3-butadiene	C5H8	68.1	0.0000	0.0000
n-Pentane	C5H12	72.2	0.0114	0.0169
trans-2-Pentene	C5H10	70.1	0.0000	0.0000
2-Methyl-2-butene	C5H10	70.1	0.0000	0.0000
3-Methyl-1,2-butadiene	C5H8	68.1	0.0000	0.0000
3,3-Dimethyl-1-butene	C6H12	84.2	0.0000	0.0000
Cyclopentane	C5H10	70.1	0.0000	0.0000
3-Methyl-1-pentene	C6H12	84.2	0.0000	0.0000
2,3-Dimethylbutane	C6H14	86.2	0.0600	0.0744
2-Methylpentane	C6H14	86.2	0.0000	0.0000
3-Methylpentane	C6H14	86.2	0.0000	0.0000
n-Hexane	C6H14	86.2	0.0370	0.0459
Methylcyclopentane	C6H12	84.2	0.0000	0.0000
2,2-Dimethylpentane	C7H16	100.2	0.0000	0.0000
Benzene	C6H6	78.1	0.0100	0.0137
Cyclohexane	C6H12	84.2	0.0000	0.0000
2,3-Dimethylpentane	C7H16	100.2	0.1020	0.1088
3-Methylhexane	C7H16	100.2	0.0000	0.0000
3-Ethylpentane	C7H16	100.2	0.0000	0.0000

Table C.13 (cont.)
Composition of a Weathered Gasoline

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial	
			Mass Fraction	Mole Fraction
2,2,4-Trimethylpentane	C8H18	114.2	0.0000	0.0000
n-Heptane	C7H16	100.2	0.0800	0.0853
Methylcyclohexane	C7H14	98.2	0.0000	0.0000
2,2-Dimethylhexane	C8H18	114.2	0.0000	0.0000
Toluene	C7H8	92.1	0.1048	0.1216
2,3,4-Trimethylpentane	C8H18	114.2	0.0000	0.0000
2-Methylheptane	C8H18	114.2	0.0500	0.0468
3-Methylheptane	C8H18	114.2	0.0000	0.0000
n-Octane	C8H18	114.2	0.0500	0.0468
2,4,4-Trimethylhexane	C9H20	128.3	0.0000	0.0000
2,2-Dimethylheptane	C9H20	128.3	0.0000	0.0000
p-Xylene	C8H10	106.2	0.1239	0.1247
m-Xylene	C8H10	106.2	0.0000	0.0000
3,3,4-Trimethylhexane	C9H20	128.3	0.0250	0.0208
o-Xylene	C8H10	106.2	0.0000	0.0000
2,2,4-Trimethylheptane	C10H22	142.3	0.0000	0.0000
3,3,5-Trimethylheptane	C10H22	142.3	0.0250	0.0188
n-Propylbenzene	C9H12	120.2	0.0829	0.0737
2,3,4-Trimethylheptane	C10H22	142.3	0.0000	0.0000
1,3,5-Trimethylbenzene	C9H12	120.2	0.0250	0.0222
1,2,4-Trimethylbenzene	C9H12	120.2	0.0250	0.0222
Methylpropylbenzene	C10H14	134.2	0.0373	0.0297
Dimethylethylbenzene	C10H14	134.2	0.0400	0.0319
1,2,4,5-Tetramethylbenzene	C10H14	134.2	0.0400	0.0319
1,2,3,4-Tetramethylbenzene	C10H14	134.2	0.0000	0.0000
1,2,4-Trimethyl-5-ethylbenzene	C11H16	148.2	0.0000	0.0000
n-Dodecane	C12H26	170.3	0.0288	0.0181
Naphthalene	C10H8	128.2	0.0100	0.0083
n-Hexylbenzene	C12H20	162.3	0.0119	0.0078
Methylnaphthalene	C11H10	142.2	0.0000	0.0000
Total			1.0000	1.0000

Johnson, P.C., Kemblowski, M.W., and Colthart, J.D. (1990b). "Quantitative analysis for the cleanup of hydrocarbon-contaminated soils by in-situ venting," *Ground Water* 28(3):413-29.

D

LIST OF REFERENCES

ABB Environmental Services, Inc. 1990. Compilation of data on the composition, physical characteristics and water solubility of fuel products. Prepared for Massachusetts Department of Environmental Protection. Job No. 6042-04. pp 1-3.

Acomb, J., D. McKay, S. Gerglund, T. Sherhart, and C. Benedikson. 1996. Estimates of mass transfer rates during air sparging using relative permeability and neutron probe measurements. Proceedings of the 1996 Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Remediation. Houston, TX. November 13-15.

Acomb, J., D. McKay, P. Currier, S. Gerglund, T. Sherhart, and C. Benedikson. 1995. Neutron probe measurements of the change in air saturation near an air sparging well. Proceedings of Battelle's Third International Symposium on In Situ and On-Site Bioreclamation. San Diego, CA. April.

Ahlfeld, D., A. Dahmani, and W. Ji. 1994. A conceptual model of field behavior of air sparging and its implications for application. *Groundwater Monitoring Review and Remediation*. Fall.

American Petroleum Institute. 1995. In situ air sparging: evaluation of petroleum industry sites and considerations for applicability, design, and operation. API Publication Number 4609. April.

Baehr, A.L. and M.F. Hult. 1988. Determination of the air-phase permeability tensor of an unsaturated zone at the Bemidji, Minnesota Research Site. U.S. Geological Survey Program on Toxic Waste. Proceedings of the Fourth Technical Meeting. Phoenix, AZ. September 25-29. Water Resour. Invest. Rep., 88-4220. pp 55-62.

Baehr, A.L. and M.F. Hult. 1992. Evaluation of unsaturated zone permeability through pneumatic tests. *Water Resources Research.* 27(10).

Baehr, A.L. and C.J. Joss. 1995. An updated model of induced airflow in the unsaturated zone. *Water Resources Research.* 31(2): 417-421.

Baker, R.S., R. Pemmireddy, and D. McKay. 1996. Evaluation of air-entry pressure during in-situ air sparging: a potentially rapid method of feasibility assessment. *Proceedings of the 1st International Symposium on In Situ Air Sparging for Site Remediation.* Las Vegas, NV. October 24-25. Potomac, MD: INET.

Barrera, J.A. 1993. Air sparging and vapor extraction as a means of removing chlorinated and BTEX compounds in complex groundwater conditions. *Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration.* Houston, TX. November 10-12. pp 541-555.

Bass, David H. 1992. Prediction of vacuum distribution along perforated pipes in soil vapor extraction application. *HMC/Superfund '92 Proceedings.* Greenbelt, MD: HMCRI. pp 894-899.

Bass, David H. 1993a. Estimation of effective cleanup radius for soil vapor extraction systems. *Journal of Soil Contamination.* 2(2): 191-202.

Bass, David H. 1993b. Scaling up vertical soil vapor extraction pilot tests to horizontal systems. *HMCRI/Superfund XIV Conference Proceedings.* Rockville, MD: HMCRI.

List of References

Bass, David H. 1998. Personal communication from David H. Bass of FDGTI to Tim Holbrook.

Bass, David H. and Richard A. Brown. 1997. Performance of air sparging systems — a review of case studies. Fourth International In Situ and On-site Bioremediation Symposium. Volume 1. New Orleans, LA. April 28-May 1.

Bass, David H, Natalie A. Lucas, and Barry A. Kline. 1993. Scaling up single-well vapor extraction pilot tests to multiple-well systems. *HMCRI/Superfund XIV Conference Proceedings.* Rockville, MD: HMCRI.

Bausmith et al. 1996. In situ air stripping. *Water Environment & Technology.* February.

Beckett, G.D. and D. Huntley. 1994. Characterization of flow parameters controlling soil vapor extraction. *Ground Water.* 32(2): 239-247.

Boardman, C.R. and J.W Skrove. 1966. Distribution in fracture permeability of a granitic rock mass following a contained nuclear explosion. *Journal of Petroleum Technology.* 18(5): 619-623

Boersma, P.M., K.R. Piontek, and P.A.B. Newman. 1995. Sparging effectiveness for groundwater restoration. *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes.* R.E. Hinchee, R.N. Miller, and P.C. Johnson (eds.). Battelle Press. pp 39-46.

Boersma, P.M., P.A.B. Newman, and K.R. Piontek. 1994. The role of groundwater sparging in hydrocarbon remediation. *Proceedings of the 1994 American Petroleum Industry Pipeline Conference.* Houston, TX. April 26-27.

Boersma, P.M., F.S. Petersen, P. Newman, and R. Huddleston. 1993. Use of groundwater sparging to effect hydrocarbon biodegradation. *Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration Conference.* Dublin, OH: National Ground Water Association. pp 557-559.

Brown, A., R.E. Payne, and P.F. Perlwitz. 1993. Air sparge pilot testing at a site contaminated with gasoline. *Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration.* Houston, TX. November 10-12. pp 429-443.

Buckingham, E. 1904. Contributions to our knowledge of the aeration of soils. U.S. Dept. Of Agriculture Soils Bur. Bull. 25.

Carslaw, H.S. and J.C. Jaeger. 1959. *Conduction of Heat in Solids.* 2nd edition. New York: Oxford University Press.

Cho, J.S. and D.C. DiGiulio. 1992. Pneumatic pumping test for soil vacuum extraction. *Environmental Progress.* 11(3): 228-233.

Clayton, W.S., R.A. Brown, and D.H. Bass. 1995. Air sparging and bioremediation: the case for in situ mixing. *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes.* R.E. Hinchee, R.N. Miller, and P.C. Johnson (eds.). Battelle Press.

Clayton W.S., D.H. Bass, N.M. Ram, and C.H. Nelson. 1996. In-situ sparging: mass transfer mechanisms. *Remediaton.* Autumn: 15-29.

Crank, J. 1975. *The Mathematics of Diffusion.* London: Oxford University Press. 2nd edition.

Crow, W.L., E.P. Anderson, and E.M. Minugh. 1987. Subsurface venting of vapors eminating from hydrocarbon product on ground water. *Ground Water Monitoring Review.* VIII(1): 51-57.

Dawson, G.W. 1994. In-well treatment for remediation of vocs in ground water. Presented at the Defense Waste Cleanup Conference. Washington, DC. November 4.

Downey, D.C. and J.F. Hall. 1994. *Test Plan and Technical Protocol For A Field Treatability Test For Bioventing — Using Soil Gas Surveys To Determine Bioventing Feasibility and Natural Attenuation Potential.* Addendum 1. U.S. Air Force Center for Enviornmental Excellence. Brooks Air Force Base, TX.

Drake, R.L. 1997. Application of integral transform techniques to subsurface convection-diffusion problems. US EPA, NRML. Ada, OK

Driscoll, F. 1975. *Ground Water and Wells.* Johnson Division, UOP Inc. St Paul, MN.

Dullien, F.A.L. 1992. *Porous Media: Fluid Transport and Pore Structure.* 2nd edition. San Diego, CA: Academic Press, Inc.

Dupont, Ryan R., Clifford J. Bruell, Douglas C. Downey, Scott G. Huling, Michael C. Marley, Robert D. Norris, and Bruce Pivetz. 1998. *Innovative Site Remediation Technology Series: Design and Application — Bioremediation.* Annapolis, MD: American Academy of Environmental Engineers. In review.

Edwards, K.B. and L.C. Jones. 1994. Air permeability from pneumatic tests in oxidized till. *Journal of Environmental Engineering.* 120(2): 329-347

Falta, R.W. 1993. Analysis of soil gas pump tests. Proc. of the ER'93 Environmental Remediation Conf. Volume 1. Augusta, GA. October 24-28. pp 441-447.

Falta, R.W. 1996. A program for analyzing transient and steady-state soil gas pump tests. *Ground Water.* 34(4): 750-755.

Fetter, C.W. 1993. *Contaminant Hydrogeology.* New York: Macmillan Publishing Co. p 458.

Felten, D., M. Leahy, L. Bealer, and B. Kline. 1992. Case study: site remediation using air sparging and soil vapor extraction. *Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration, Eastern Regional Ground Water Issues.* Houston, TX. November 4-6. pp 395-411.

Fischer, J.M., T.P. Wilson, and A.C. Kane. 1995. Air-sparging and in situ bioremediation research at Picatinny Arsenal, New Jersey. Presented at First Annual Strategic Environmental Research and Development Program (SERDP) Symposium. Washington, DC. April 12-14.

Fulton, D.E. 1995. Techniques for successfully implementing in-situ remediation systems. *Remediation.* 5(4): 37-47.

Gould, T.F. and S.E. Sexton. 1996. Annual report: building 1168 treatability study, Fort Wainwright, Alaska. Harding Lawson Associates, Anchorage, AL. Prepared for U.S. Army Corps of Engineers, Alaska District.

Govind, R., V. Utgikar, W. Zhao, Y. Shan, and M. Parvatiyar. 1994. Development of novel biofilters for treatment of volatile organic compounds. Proceedings: IGT Symposium on Gas, Oil, and Environmental Technology. Colorado Springs, CO. Chicago, IL: Institute of Gas Technology. November 29-December 3.

Greacen, E.L., R.L. Correll, R.B. Cunningham, G.G. Johns, and K.D. Nicolls. 1981. Chapter 6. *Soil Water Assessment by the Neutron Method.* E.L. Gracen (ed.). CSIRO, East Melbourne, Victoria, Australia.

Hantush, M.S. 1964. Hydraulics of wells. *Advances in Hydroscience.* San Diego, CA: Academic. Volume 1: 281-442

Hauge, L. 1991. Adaptation of a commercial groundwater flow model to soil vapor extraction system modeling. MSCE Thesis. Michigan Technological University, Houghton, MI.

Heath, J.S., K. Koblis, S.L. Sager, and C. Day. 1993. Risk assessment for total petroleum hydrocarbons. *Hydrocarbon Contaminated Soils — Volume III.* E.J. Calabrese and P.T. Kostecki (eds.). Chelsea, MI: Lewis Publishers. pp 267-301.

Hein, G. 1996. Air sparging as a remediation technique: modelling and experimental analyses. Ph.D. Dissertation. Michigan Technological University, Houghton, MI. April.

Hein, G.L., J.S. Gierke, N.J. Hutzler, and R.W. Falta. 1997. Three-dimensional experimental testing of a two-phase, flow-modelling approach for air sparging. *Ground Water Monitoring and Remediation.* Summer. In Press.

Hinchee, R.E., S.K. Ong, R.N. Miller, D.C. Downey, and R. Franot. 1992. *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing*. U.S. Air Force Center for Environmental Excellence.

Hodnett, M.G. and J.P. Bell. 1991. Neutron probe standards: transport sheilds or a large drum of water? *Soil Sci.* 151(2): 133-120.

Hubbert, M.K. 1940. The theory of groundwater motion. *J. Geol.* 38(8): 785-944

Hutzler, N.J., B.E. Murphy, and J.S. Gierke. 1990. *State of Technology Review: Soil Vapor Extraction Systems.* EPA600/2-89-024. Risk Reduction Engineering Laboratory, US EPA, Cincinnati, OH. January.

Ji, W., A. Dahmani, D. Ahlfeld, J. Lin, and E. Hill. 1993. Laboratory study of air sparging: air flow visualization. *Groundwater Monitoring Review and Remediation*. Fall. pp 115-126.

Johnson, P.C. and A.J. Stabenau. 1991. *HyperVentilate — A Software Guidance System Created for Vapor Extraction Applications*. Shell Oil Company.

Johnson, P.C., M.W. Kemblowski, and J.D. Colthart. 1988. Practical screening models for soil venting applications. *NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater.* Houston, TX. pp 521-546.

Johnson, P.C., M.W. Kemblowski, and J.D. Colthart. 1990. Quantitative analysis for the cleanup of hydrocarbon-contaminated soils by in-situ venting. *Ground Water.* 28(3): 413-429.

Johnson, Paul C., Arthur Baehr, Richard A. Brown, Robert Hinchee, and George Hoag. 1994. Innovative Site Remediation Technology — Vacuum Vapor. Annapolis, MD: American Academy of Environmental Engineers.

Johnson, P.C., C.C. Stanley, D.L. Byers, D.A. Benson, and M.A. Acton. 1991. Soil venting at a California site: field data reconciled with theory. *Hydrocarbon Contaminated Soils and Groundwater.* Volume 1. P.T. Kostecki and E.J. Calabrese (eds.). Boca Raton, FL: Lewis Publishers. pp 274-275.

Johnson, P.C., C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart. 1990. A practical approach to the design, operation, and monitoring of in situ soil-venting systems. *Ground Water Monitoring and Remediation.* Spring: 159-177.

Johnson, P.C., R.L. Johnston, C. Neaville, E.E. Hansen, S.M. Stearns, and I.J. Dortch. 1995. Do conventional monitoring practices indicate in situ air sparging performance. *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes.* R.E. Hinchee, R.N. Miller, and P.C. Johnson (eds.). Battelle Press.

Johnson, R., W. Bagby, M. Perrott, and C. Chen. 1992. Experimental examination of integrated soil vapor extraction techniques. *Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration, Eastern Regional Ground Water Issues.* Houston, TX. November 4-6. pp 441-452.

Johnson, R.L. 1994. Enhancing biodegradation with in-situ air sparging; a conceptual model. *Air Sparging for Site Remediation*. R.E. Hinchee (ed.). Boca Raton, FL: Lewis Publishers.

Johnson, R.L., P.C. Johnson, D.B. McWhorter, R.E. Hinchee, and I. Goodman. 1993. An overview of in situ air sparging. *Ground Water Monitoring and Remediation*. Fall. pp 127-135.

Joss, C.J. and A.L. Baehr. 1995a. AIR2D — a computer program to simulate two dimensional axisymmetric air flow in the unsaturated zone. U.S. Geological Survey Open File Report.

Joss, C.J. and A.L. Baehr. 1995b. Documentation of AIR3D — an adaptation of the ground-water-flow code MODFLOW to simulate three-dimensional air flow in the unsaturated zone. U.S. Geological Survey Open-File Report 94-533.

Kampbell, D.H., J.T. Wilson, and C.J. Griffin. 1992. Performance of bioventing at Traverse City, MI. Symposium on Bioremediation of Hazardous Wastes. US EPA, Chicago, IL. May 4-6.

Kane, A.C., J.M. Fischer, and T.P. Wilson. 1996. Microcosm study to determine optimum levels of oxygen and methane for cometabolic biodegradation of trichloroethylene in sediment and ground water from Picatinny Arsenal, Morris County, New Jersey. Presented at AGU Spring Meeting, Baltimore, MD. May 20-24.

Kirkham, D. 1946. Field method for determination of air permeability of soil in its undisturbed state. *Soil Sci. Soc. Am. Proc.* 11: 93-99

Kittel, J.A., R.E. Hinchee, R. Hoeppel, and R. Miller. 1994. Bioslurping — vacuum-enhanced free product recovery coupled with bioventing: a case study. *Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Groundwater.* Houston, TX. November 2-4.

Klinkenberg, L.J. 1941. The permeability of porous media to liquids and gases. *Drilling and Production Practice*. New York: American Petroleum Institute. pp 200-213.

Kosky, K.F. and C.R. Neff. 1988. Innovative biological degradation system for hydrocarbons treatment. Proceedings: Petroleum Hydrocarbons and Organic Chemicals in Ground Water. Houston, TX. Dublin, OH: NWWA. November.

Leonard, W. and R. Brown. 1992. Air sparging: an optimal solution. *Proceedings of the Conference Entitled Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration, Eastern Regional Ground Water Issues*. Houston, TX. November 4-6. pp 349-363.

Little, Arthur D. 1987. *The Installation Restoration Program Toxicology Guide, Volume 1.* Section 2: 1-16.

Lundegard, P.D. 1995. Air sparging: much ado about mounding. *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes*. R.E. Hinchee, R.N. Miller, and P.C. Johnson (eds.). Battelle Press.

Lundegard, P.D. and G. Andersen. 1993. Numerical simulation of air sparging performance. *Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration.* Houston, TX. November 10-12. pp 461-476.

Lundegard, P.D. and G. Andersen. 1996. Multiphase numerical simulation of air sparging performance. *Ground Water.* 34(3): 451-460.

Lundegard, P.D., B. Chaffee, and D. LaBrecque. 1996. Effective design of a horizontal air sparging well. *Proceedings of the 1996 Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Remediation*. Houston, TX. November 13-15.

Marley, M., D. Hazebrouck, and M. Walsh. 1992. The application of in situ air sparging as an innovative soils and groundwater remediation technology. *Groundwater Monitoring and Review*. Spring: 137-145.

List of References

U.S. Army Corps of Engineers (US ACE). 1997. *Air Sparging Engineer Manual.* (EM 1110-1-4005). Engineer Technical Letter. Missouri River Division, Omaha, NE. September 15, 1997.

U.S. Department of Energy (DOE). 1994. *Department of Energy, Cost Estimating Guide.* Volume 6. Office of Infrastructure Acquistion (FM-50).

U.S. Department of Energy (DOE). 1995. *Department of Energy, Professional Skills Training.* Project Management Series. Cost and Schedule Estimation and Analysis (PMMS2).

US EPA. 1989. *Methods for Evaluating the Attainment of Cleanup Standards, Volume 1: Soil and Soils Media.* Office of Solid Waste and Emergency Response, Washington, DC.

US EPA. 1991a. *Engineering Bulletin: In Situ Soil Vapor Extraction.* EPA/540/2-91/006. May.

US EPA. 1991b. *Guide for Conducting Treatability Studies under CERCLA: Soil Vapor Extraction.* EPA/540/2-91/019A. Risk Reduction Engineering Laboratory, USEPA, Cincinnati, OH. September.

US EPA. 1994. *Soil Vapor Extraction Treatment Technology Resource Guide.* EPA/542-B-94-007. September.

US EPA. 1995. *Soil Vapor Extraction Enhancement Technology Resource Guide.* EPA/542-B-95-003. October.

US EPA. 1996. *Assessing UST Corrective Action Technologies: Diagnostic Evaluation of In-Situ SVE-Based System Performance.* US EPA 600/R-96/041. March 1996.

US EPA. 1997. *Engineering Analysis of Selected Soil Vapor Extraction Enhancement Technologies.* Technology Innovation Office, Office of Solid Waste and Emergency Response, Washington, DC. EPA 542-R-97-007. September.

Van Bavel, C.H.M. and G.B. Stirk. 1967. Soil water measurement with an ^{241}Am-Be neutron source and an application to evaporimetry. *J. Hydrol.* 5:40-46.

Veenis, M.M., D.H. Bass, and P.G. Bartholomae. 1997. Biodegradation rates estimated from groundwater temperature rise during air sparging. Fourth International In Situ and On-site Bioremediation Symposium. Volume 2. New Orleans, LA. April 28-May 1.

Wade, A. 1996. Performance comparisons between a horizontal and a vertical air sparging well: a full-scale one-year pilot study. Sixth Combined Innovative Technology Transfer and Chemists' Workshop. USACE. Las Vegas, NV. April 8-12.

Weeks, E.P. 1978. Field determination of vertical permeability to air in the unsaturated zone. U.S. Geological Survey Professional Paper 1051.

Wilson, J.T. and B.H. Wilson. 1985. Biotransformation of trichloroethylene in soil. *Appl. Environ. Micro.* 49(1): 242-243.

Wisconsin Department of Natural Resources. 1993. *Guidance for Design, Installation, and Operation of In Situ Air Sparging Systems.* Publ-SW186-93. Madison, WI.

World Health Organization, International Agency for Research on Cancer. 1989. IARC monographs on the evaulation of carcinogenic risks to humans — occupational exposures in petroleum refining; crude oil and major petroleum fuels. Volume 45. Lyon, France: IRAC.

Yu, L.L. 1985. Study of air flow through porous media. M.S. thesis. Dept. of Civ. Eng., Univ. of Conn., Storrs.

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