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of Engineers®

**ENGINEERING AND DESIGN**

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# Soil Vapor Extraction and Bioventing

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**ENGINEER MANUAL**

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Manual  
No. 1110-1-4001

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Engineering and Design  
SOIL VAPOR EXTRACTION AND BIOVENTING

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## Chapter 1 Introduction

### 1-1. Purpose

This manual provides practical guidance for the design and operation of soil vapor extraction (SVE) and bioventing (BV) systems. It is intended for use by engineers, geologists, hydrogeologists, and soil scientists, chemists, project managers, and others who possess a technical education and some design experience but only the broadest familiarity with SVE or BV systems.

### 1-2. Applicability

This manual applies to HQUSACE elements, major subordinate commands (MSC), districts, laboratories, and field operating activities (FOA) having hazardous, toxic, or radioactive waste responsibilities.

### 1-3. References

The manual does not present a detailed, comprehensive discussion of each and every factor associated with SVE or BV systems. Such a presentation would require many volumes. However, there are several publications which provide excellent summaries of design factors and operational details. An extensive listing of books and journal articles pertaining to SVE and BV is presented in Appendix A. Of these references, the following are suggested as key supplementary sources of information for design and operation of SVE or BV systems.

| Subject             | Reference            |
|---------------------|----------------------|
| Technology overview | Holbrook et al. 1998 |
|                     | Johnson et al. 1994  |
|                     | USEPA 1989a          |
|                     | USEPA 1991d          |
|                     | USEPA 1992a          |
|                     | USEPA 1995b          |

|   |  |
|---|--|
| Important physical, biological, and chemical parameters | ASTM D5126-90<br>Corey 1986a<br>DePaoli et al. 1991c<br>Downey and Hall 1994<br>Johnson, Kembrowski, and Colthart 1990b<br>Ostendorf and Kampbell 1991<br>USEPA 1986<br>USEPA 1991c  |
| Pilot testing and design                                | DiGuilio et al. 1990<br>Hinchee et al. 1992<br>Holbrook et al. 1998<br>Johnson et al. 1990a<br>Johnson and Ettinger 1994<br>Sayles et al. 1992<br>US EPA 1995a   |
| Modeling  | Baehr, Hoag, and Marley 1989<br>Becket and Huntley 1994<br>DePaoli et al. 1991b<br>DePaoli et al. 1991c<br>Falta, Pruess, and Chestnut 1993<br>King 1968<br>Marley et al. 1990a<br>Massmann 1989<br>McWhorter 1990<br>Muskat and Botset 1931<br>Rathfelder, Yeh, and Mackay 1991<br>Shan, Falta, and Javandel 1992<br>USEPA 1993c<br>Wilson, Clarke, and Clarke 1988 |
| Equipment specification and operation                   | DePaoli et al. 1991b<br>Johnson et al. 1990a<br>USEPA 1992a<br>USEPA 1993c   |

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Evaluation of system performance      CEGS 01810 Commissioning and Demonstration for Soil Vapor  
Extraction (SVE) Systems  
CEGS 02150 Piping; Off-Gas  
CEGS 11215 Fans/Blowers/Pumps; Off-Gas  
DePaoli et al. 1991b  
DePaoli et al. 1991c  
Holbrook et al. 1998  
Peargin and Mohr 1994  
Travis and Macinnis 1992  
USEPA 1989a  
USEPA 1989b  
USEPA 1990a  
USEPA 1992a

Associated Technologies and      In-Situ Air Sparging: USACE EM 1110-1-4005  
Enhancements      Air Sparging: Holbrook, et. al. 1998  
Multi-Phase Extraction: USACE EM 1110-1-4010  
Analysis of Selected Enhancements to SVE: USEPA 1997a, 1997b

Additional, updated references are available on the internet, including the following website maintained by the USACE: <http://www.environmental.usace.army.mil/info/technical/geotech/sve/sve.html>

There are many periodicals that frequently include research and case studies pertaining to SVE and BV. Some of these are:

*Environmental Protection;*  
*Environmental Science and Technology;*  
*Ground Water* (Association of Ground Water Scientists and Engineers);  
*Ground Water Monitoring and Remediation* (Association of Ground Water Scientists and Engineers);  
*Hazardous Materials Control;*  
*Hazardous Waste and Hazardous Materials;*  
*Journal of Contaminant Hydrology;*  
*Journal of Environmental Engineering* (American Society of Civil Engineers);  
*Journal of Hazardous Materials;*  
*Pollution Engineering;*  
*Remediation, Journal of Environmental Cleanup Cost, Technologies & Techniques;*  
*The National Environmental Journal;* and  
*Water Resources Research* (American Geophysical Union).

#### 1-4. Background

Groundwater contamination by petroleum products and organic solvents is a serious problem in industrialized countries. Underground petroleum storage tanks (USTs) account for a large portion of the problem. In 1993, the U.S. Environmental Protection Agency (USEPA) estimated that of the 2 million USTs in the United States, more than 10 percent, or about 295,000, are leaking (USEPA 1993a). In addition, surface spills, pipeline leaks, and releases from pits, ponds, and lagoons have contributed to this contamination problem.

*a.* Residual volatile organic compounds (VOCs) constitute an ongoing source of contamination of soil and groundwater. Emphasis has recently been placed on removing this long-term contamination source in addition to mitigating immediate effects. In situ solutions are also increasingly favored for their economic advantages.

*b.* SVE is one of the most effective and cost-efficient methods of removing VOCs from unsaturated soils. An SVE system consists of one or more extraction wells screened in the unsaturated zone, blowers or vacuum pumps, and often also includes air injection or pressure venting wells, a low permeability cap at the ground surface, an air/water separator, and an offgas treatment system.

*c.* Airflow is induced in the unsaturated zone by creating a pressure gradient through the injection or withdrawal of air from wells or trenches in the subsurface. SVE systems usually withdraw air for subsequent treatment by adsorption on granular activated carbon (GAC), catalytic oxidation, or other processes. The SVE gas flow enhances evaporation of nonaqueous phase liquids (NAPL), volatilization of contaminants dissolved in pore water, and desorption of contaminants from the surfaces of soil particles.

*d.* Major limitations of SVE are the need, at some locations, for offgas treatment, and the inability to extract semivolatile organic compounds (SVOCs) (Dupont, Doucette, and Hinchee 1991; USEPA 1988a). Costs for offgas treatment can exceed 50 percent of total SVE remediation costs (Reisinger, Johnstone, and Hubbard 1994).

*e.* BV is similar to SVE in that air is made to flow through the subsurface, but treatment of contaminants takes place in situ rather than aboveground, thereby reducing remediation costs. Naturally occurring microorganisms in the unsaturated zone biodegrade the contaminants. BV airflow rates need to be sufficient to provide oxygen to the microorganisms, which are usually oxygen limited, but slow enough to allow sufficient contaminant residence times in the subsurface and minimize volatilization losses to areas outside the treatment zone. BV does not rely on volatilization, and therefore is appropriate for semi-volatile compounds that are aerobically biodegradable, as it focuses on the treatment of soil contaminants and soil vapors within the unsaturated zone prior to their release to the atmosphere. A BV system consists of one or more extraction or injection wells screened in the unsaturated zone, blowers or vacuum pumps, and often also includes air injection or pressure venting wells.

*f.* In the United States, SVE is an accepted technology that has been used at landfill sites and at leaking UST sites since the 1970s. As early as 1972, Duane Knopik began employing SVE to clean up leaked gasoline from a UST at his service station in Forest Lake, Minnesota. By 1982, Knopik had employed his by then-patented system (see paragraph 11-2) at approximately 100 installations throughout the United States. Other early developers of SVE systems in the late 1970s and early 1980s included Oil Recovery Systems, Exxon Company USA, Shell Oil Company, Upjohn Company, and the American

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Petroleum Institute (Thornton and Wootan 1982; U.S. District Court 1994). Soil venting, which includes air extraction and injection, is the primary method used in the United States to remove VOCs from the unsaturated subsurface. SVE, which always involves air extraction but may include air injection, is considered a presumptive remedy for VOCs in the USEPA's Superfund program, meaning that a detailed technology screening process is not necessary for implementation. In 1997, SVE was applied or planned to be applied at 27% of Superfund sites (USEPA 1999). Since this statistic does not include bioventing, application of venting (i.e., including both SVE and bioventing) at Superfund sites likely exceeds 30%. Thus, its frequency of use is second only to groundwater pump and treat. A majority (69 percent) of the total volume of soil at Superfund remediation actions is treated by SVE (USEPA 1999). The popularity and widespread use of venting is due to its simplicity of operation and proven ability to remove contaminant mass inexpensively compared to competing technologies.

g. Evidence of unsaturated zone biodegradation resulting from air advection was first reported by the Texas Research Institute (1980; 1984). During the same period, researchers conducting experiments for Shell Research in the Netherlands made the first field observations of venting-induced biodegradation (van Eyk and Vreeken 1988). In the late 1980s and early 1990s, the U.S. Air Force (USAF) carried out field-scale SVE and bioventing research at several bases, including Hill AFB in Utah and Tyndall AFB in Florida (DePaoli et al. 1991a, 1991b, 1999c; Miller et al. 1991). This work was expanded to include bioventing testing at >125 sites, in an effort the Air Force Center for Environmental Excellence (AFCEE) termed their Bioventing Initiative (Miller et al. 1993; AFCEE 1996). The USAF now considers bioventing to be a presumptive remedy for jet fuel-contaminated sites.

## 1-5. Scope

This manual deals with all aspects of the engineering of SVE/BV systems, including site characterization, technology selection, bench- and pilot-scale testing, design, installation, operation, and closure.

a. When this Engineer Manual was first prepared in 1995, SVE and BV were relatively new technologies. The basic physical principles governing SVE are fairly well understood, but details of system design were, and still are often determined empirically rather than by rigorous analysis (Massmann 1989; Johnson et al. 1990a). This document attempts to normalize the approach to design and implementation of SVE/BV. Since 1995, several important documents have been published expanding the knowledge base for this technology. These include:

- A WASTECH monograph entitled Vapor Extraction and Air Sparging (Holbrook et al. 1998) was authored by some of the leading authorities on air based remediation systems. WASTECH is a multiorganization effort which joins in partnership professions, societies of soil scientists, microbiologists, and chemical, civil and mechanical engineers; U.S. EPA, DOD, and DOE; and a number of other organization that address hazardous waste issues. This monograph, sponsored in part by U.S. EPA's Technology Innovation Office covers the design, applications and implementation of SVE, bioventing and air sparging. It places particular emphasis on enhancements to these technologies.
- Recommendations stemming from AFCEE's Bioventing Initiative are provided as guidance in Principles and Practices of Bioventing (Leeson and Hinchee 1995). AFCEE has included in this document guidance from their extensive experience from performing and monitoring BV at hundreds of sites.

- U.S. EPA's "Analysis of Selected Enhancements for Soil Vapor Extraction" (USEPA 1997a), a comprehensive engineering report describing the status of and evaluating Air Sparging, Dual-Phase Extraction, Direction Drilling, Pneumatic and Hydraulic Fracturing, and Thermal Enhancements as methods for aiding remediation of sites otherwise addressed by SVE.
- USACE's Engineer Manuals on In Situ Air Sparging (1110-1-4005) and Multi-Phase Extraction (1110-1-4010). These manuals, discussed briefly in this manual, expand upon the engineering guidance provided in the original SVE/BV EM by describing the physics and application of these related air based remediation technologies.

*b.* This SVE/BV EM intends to capture the advances of the state-of-the-science that have been presented in the foregoing documents and in the peer reviewed literature to upgrade the engineering guidance originally developed in 1995.

*c.* Although various models are discussed within pertinent sections, exhaustive coverage of analytical and numerical modeling relevant to SVE and BV systems is beyond the scope of the manual. Information on a wide range of available models is summarized in Appendix C.

## **1-6. Organization**

*a.* The manual is intended to be as helpful as possible to the designer/operator of SVE/BV systems. Material is organized sequentially, so that the reader can conveniently begin using it at any stage of an SVE/BV project. It is recommended that regardless of the stage of the project at hand, Chapter 3 be reviewed first if there is any question as to whether selection of SVE/BV at a given site is appropriate. The design process is summarized in a set of decision trees, and case examples are presented for each major topic.

*b.* The manual provides the guiding principles and thought processes for engineering SVE/BV systems. The numerous site-specific conditions which come into play in any given SVE/BV situation preclude a simple cookbook approach. System design is as much an art as a science, and system modifications are necessary as new information becomes available or site conditions change.

## **1-7. Tools and Resources**

A variety of tools and resources are available to assist the SVE and BV practitioner. These include models for design and optimization of systems, technical journals and publications which summarize case studies and recent technical developments, and electronic bulletin boards which summarize technical developments and vendor information. New SVE and BV techniques are continually being developed. Therefore, a review of the latest case studies, models, and references prior to designing an SVE/BV system is recommended.

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*a.* Models. Analytical and numerical models can be used to:

- Determine applicability of various SVE and BV configurations during the technology screening process.
- Aid in design of pilot test programs.
- Extrapolate pilot test data to design of full-scale systems.
- Estimate airflow rates and contaminant concentrations to aid in equipment specification.
- Optimize the numbers and locations of air extraction and injection points.
- Estimate the time that will be required to meet remedial objectives.
- For BV, determine kinetic parameters of biodegradation.

(1) Models should not be used in place of pilot testing because subsurface systems usually include variations in permeability, moisture content, and contaminant concentrations, and may include man-made conduits which are not detected during site investigations and are, therefore, not simulated in models. These variations are frequently detected during the pilot-testing process and become important to the design and successful operation of full-scale systems. Models are also based on specific assumptions (e.g., site homogeneity, boundary conditions, absence of layers) that do not match site conditions.

(2) Models range from commercially available, user friendly computer programs to complicated, uncompiled computer code requiring substantial programming ability. Models may be divided into three categories:

- Models that simulate pressure distributions and airflow.
- Models that simulate contaminant, oxygen, and other vapor concentrations.
- Models that simulate both pressure distributions and vapor concentrations.

(3) Reference will be made throughout the manual, where appropriate, to models that may be useful for the task being discussed. Appendix C summarizes the models that are currently available, including their applications, limitations, and ease of use.

*b.* Other useful sources of information. Computer databases, electronic bulletin board systems (BBS), and expert systems are available to provide information on the latest remediation technology developments, available software, and new publications.

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(1) Several offices and technical laboratories within the USEPA provide special computer bulletin boards related to soil and groundwater remediation technologies. Specifically, the USEPA, Office of Research and Development (ORD: Cincinnati, Ohio) offers a BBS called CLU-IN that provides access to forums, databases, modeling software, and technical articles on innovative technologies for soil and groundwater remediation at Superfund sites. The CLU-IN web site address is <http://www.clu-in.org/>.

(2) USACE Hazardous, Toxic, and Radioactive Waste Center of Expertise (HTRW-CX) has designed a computer-based information system entitled Lessons Learned. This system was created to facilitate the exchange of information among multidisciplinary USACE elements; to collect ideas on solutions, new technology, and better methods; and to distribute those lessons learned to system users. The database requires a PC with MSDOS v.3.0 or later, with at least 400k available RAM, and 2 megabytes free space, and a modem (Hayes compatible unless file transfers can be accomplished without one). For additional information contact the HTRW-CX staff at:

Web site: <http://hq.environmental.usace.army.mil/tools/lessons/list/list.html>

(3) Other Federal agencies and research organizations also provide BBS and electronic databases. A number of useful links may be found at the following web site maintained by USACE:  
<http://www.environmental.usace.army.mil/info/technical/geotech/sve/sve.html>

(4) The USEPA's RCRA/Superfund Hotline (800-424-9346) is a source of additional information on SVE and BV.

## Chapter 2 Strategy for Using SVE/BV

### 2-1. Introduction

This chapter outlines the overall strategy for using SVE/BV and reviews the underlying principles of contaminant transport and removal. The physical and chemical properties of contaminants that influence their fate and movement are identified and introduced, as are the pertinent soil properties. A brief primer on vapor transport through soil is also provided.

### 2-2. SVE/BV Application Strategy

A phased approach is recommended in applying SVE or BV.

*a.* If early stages of evaluation indicate that these technologies are not applicable to a site, a change in course can be made before expending unnecessary resources. Figure 2-1 broadly summarizes the process whereby the project team undertakes screening and bench- and pilot-scale testing. Given favorable results, the team then designs the full-scale system, starts it up, performs operations and maintenance, and, at the appropriate time, shuts the system down. Figure 2-1 also presents the primary considerations that enter into each step of the phased approach. It assumes that basic site characterization addressing the nature and extent of contamination and hydrogeological setting has been completed.

*b.* Applying the appropriate human resources is an essential component of the SVE/BV strategy. Depending on the particular phase of the project being confronted, and on site-specific conditions and objectives, a variety of staff specialists may need to be involved. These will likely include one or more engineers, geologists, hydrogeologists, soil scientists, and chemists. Even in a relatively small project, assembling a project team appropriate for the problem is essential. Not all team members would work extensively on the project, rather they may just consult on specific issues, but their input may be very important to achieving success. A diverse team is best able to identify the information needed to make decisions as early as possible. EM 200-1-2 provides additional guidance regarding project planning.

### 2-3. Fundamental Principles

The factors that determine vapor phase contaminant fate and transport in the unsaturated zone are summarized below. Contaminant transport and removal, contaminant characteristics, porous medium characteristics, and principles of vapor flow are described. See USEPA 1991b for a more complete discussion of this material.

*a. Contaminant transport and removal.* The removal of VOCs and SVOCs by SVE/BV can be controlled by a number of processes. Transport and removal mechanisms include advection, volatilization, desorption, biodegradation, and diffusion. Figure 2-2 illustrates the processes that occur in soil contaminated by VOCs and the mechanisms of contaminant removal (USEPA 1991c). In the hypothetical example illustrated, VOCs exist in the vadose zone as residual nonaqueous phase liquid (NAPL) retained by capillary forces between solid particles; as adsorbed organics associated with solid surfaces; as dissolved

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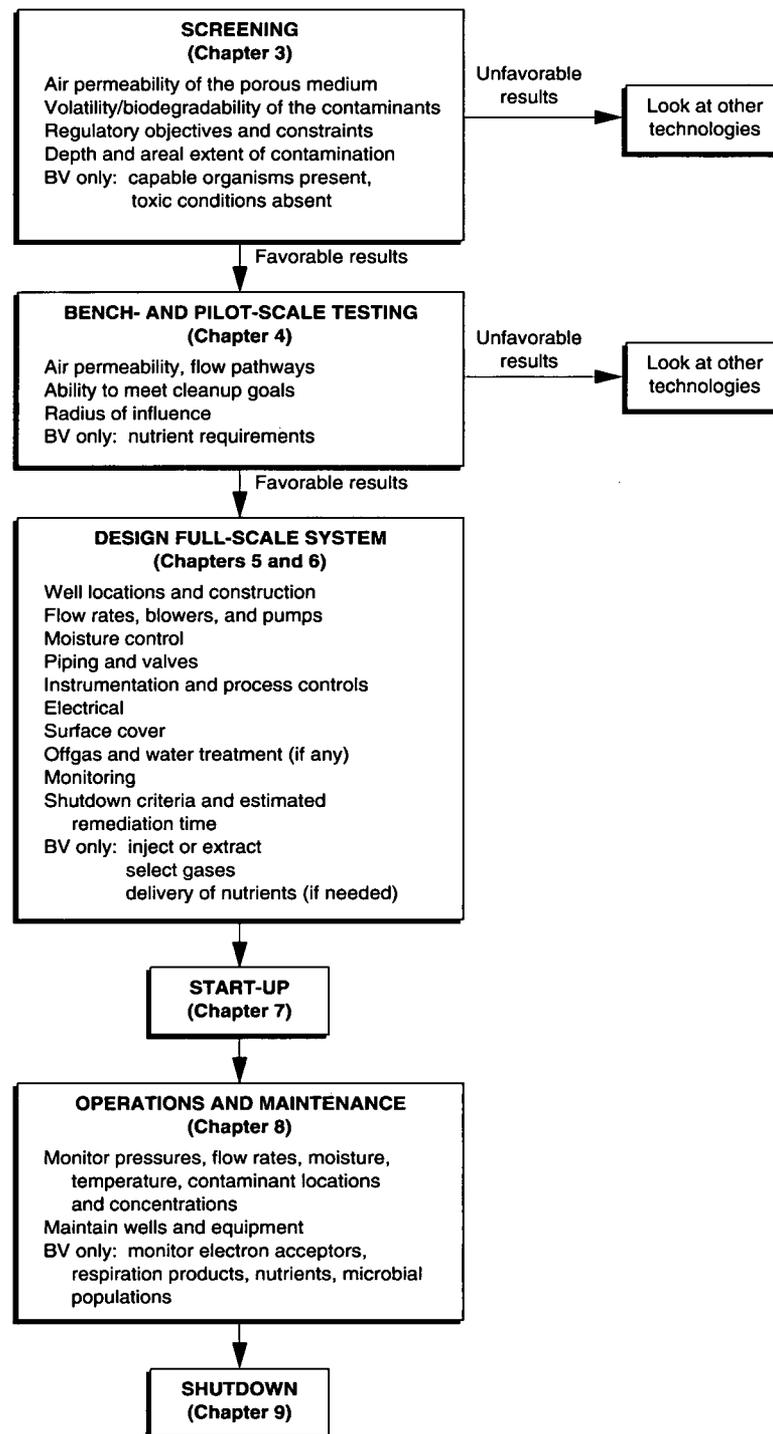


Figure 2-1 SVE/BV Application Strategy

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organics in soil pore water; and as free organic vapor in the soil pore gas. The distribution of VOCs among liquid, solid, and gaseous phases is governed by various physical phenomena as described in paragraph 2-3*b*. Figure 2-2 also depicts light NAPL (LNAPL) within the capillary fringe and pooled on the water table, as well as pools of dense NAPL (DNAPL) pooled below the water table within depressions in the bedrock surface. Where both LNAPL and DNAPL compounds are present at the same site, co-solvation of one within the other may occur.

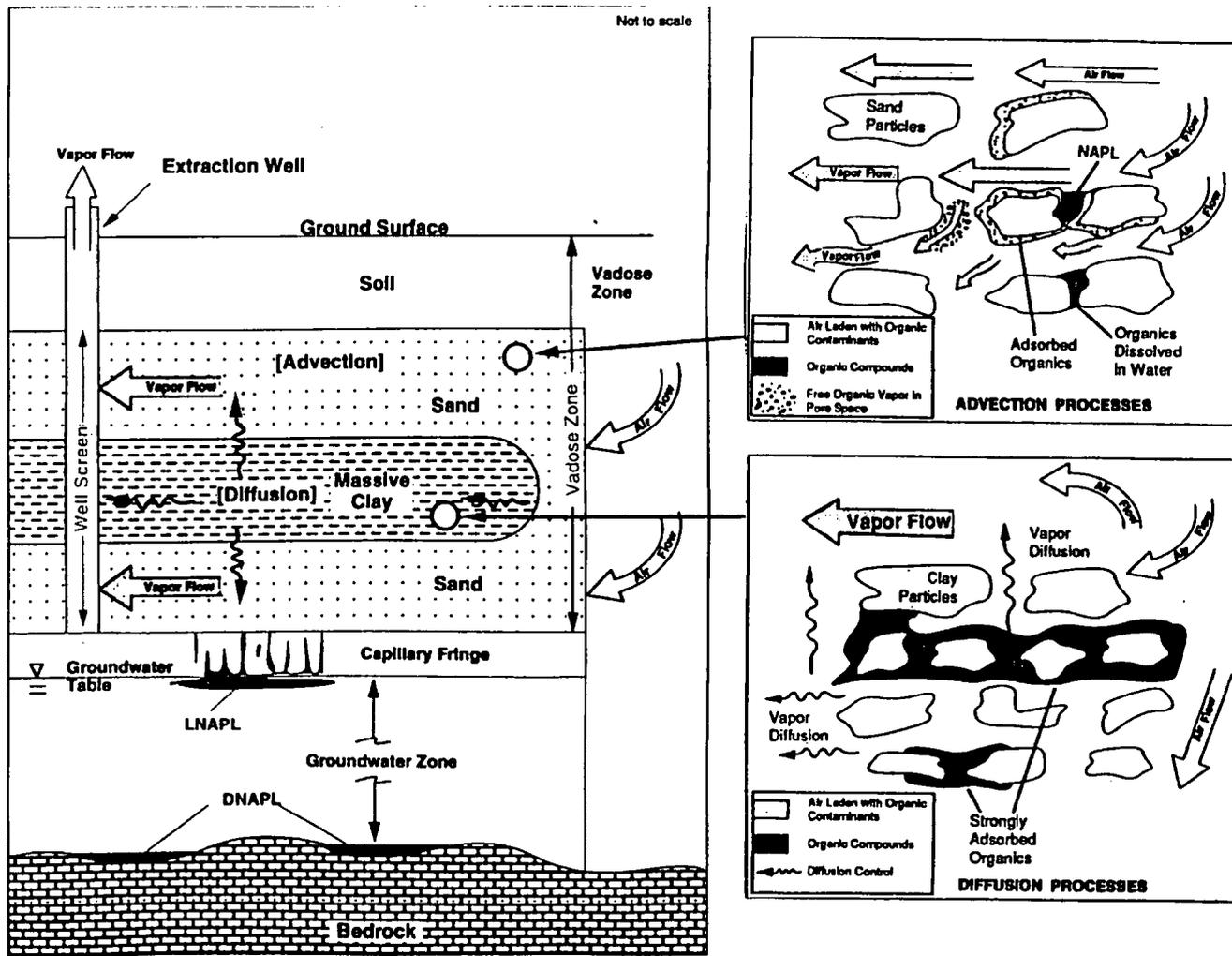
(1) As air is drawn through the soil during SVE/BV, contaminants that volatilize into the vapor phase are carried along with the bulk movement of the air through more permeable regions in a process known as advection. Advection through low permeability regions is relatively slow. However, where concentration gradients exist between pores being swept by the flowing air and contaminated soil not in communication with the airstream, contaminants will move by diffusion toward the flowing air. Generally, diffusion is much slower than advection and will limit the rate of contaminant removal from less permeable zones.

(2) Fastest removal rates theoretically would occur in cases where contaminants are fully volatilized and reside in interconnected soil pores. In such a situation, removal would be limited by the advection rate, and the removal rate could be increased simply by increasing the airflow rate. This is hardly ever the case, however, and other factors usually limit contaminant removal rates. The rate of volatilization of contaminants from a NAPL or an aqueous phase is often limiting. Desorption of contaminants from soil particle surfaces can also be the limiting process (Novak, Young, and Forsling 1993). Nonequilibrium effects are further discussed in paragraph 2-3*b*, and their manifestations are presented in paragraph 9-9. The following paragraphs underscore the importance of recognizing and designing for nonequilibrium conditions.

(3) Johnson, Palmer, and Keely (1987) studied the effect of soil moisture on the diffusion of VOCs in soil columns. Travel times were two to three times longer in damp sand than in dry sand. The delay was attributed to the effect of partitioning to the pore water. Many sites with LNAPL such as gasoline or fuel oil will have a zone of residual contamination in the vicinity of the water table and capillary fringe. Diffusion of contaminants to the overlying unsaturated zone is often the limiting transport mechanism at such sites.

(4) On a larger scale, contaminant removal at a site will generally commence in more permeable zones and proceed to progressively less permeable zones. Soil stratigraphy will in this sense limit contaminant removal. Clay lenses containing NAPL, for example, can serve as continuing sources of vapor phase contaminants long after adjacent, more permeable zones have been remediated. Stratigraphy is extremely important to consider in designing the remediation system and projecting completion times.

(5) There is a risk to "overdesign" SVE systems, using higher venting flow rates than necessary (Payne 1993). In many cases, higher flow rates do not improve removal but do increase offgas treatment costs. To design SVE and BV systems as economically as possible, venting flow rates should be minimized in order to reduce offgas volumes and maximize contaminant concentrations in the offgas, thereby maximizing contaminant removal per unit cost of moving air. This should be carefully weighed against the competing need to provide adequate air flow between air extraction and injection points to find an optimal operating point. To achieve adequate air flow between wells, it is often necessary to induce large air flows near the extraction or injection wells. It is desirable to identify the removal rate-limiting step at a site and determine the minimum venting flow rates which will effectively remediate the site, as discussed further in Chapters 5 and 9.



Source: after USEPA 1991c

Figure 2-2 SVE Transport Processes

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*b. Contaminant properties.* Physical and chemical properties strongly influence the fate and transport of contaminants. These properties affect the distribution of the contaminants among the four phases in which they can exist in soil, namely as vapor (gaseous phase), dissolved in pore water (aqueous phase), adsorbed on the surface of particles (solid phase), and as NAPL (Figure 2-3). The degree to which a compound partitions into the vapor phase, at equilibrium, is indicated by the compound's vapor pressure, Henry's law constant, and boiling point. The degree to which a compound, at equilibrium, will dissolve in water is described by the compound's solubility. Finally, the degree to which a compound, at equilibrium, will adsorb to soil is indicated by the soil adsorption coefficient. In a mixture of contaminants (such as a petroleum product) the distribution of compounds among the four phases will change as weathering occurs over time after its release into the environment. Early on, the lighter, more volatile, and more soluble fractions tend preferentially to be subject to various removal mechanisms. The heavier, less soluble, and less volatile fractions, meanwhile, have a greater tendency to persist in association with the soil matrix. Appendix B provides a compendium of tables listing contaminant properties.

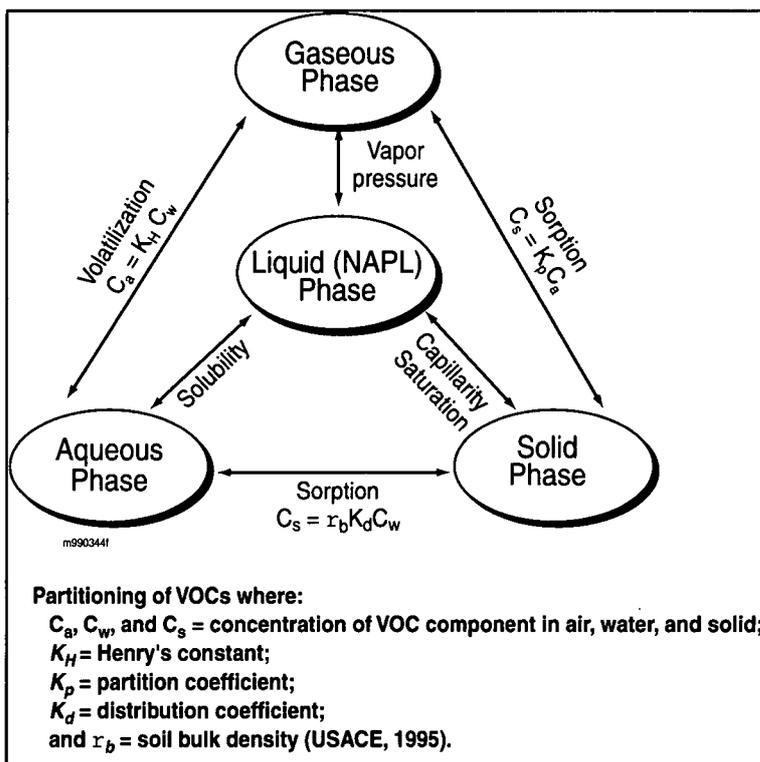


Figure 2-3 Partitioning of VOCs

(1) Vapor pressure is the tendency of a solid or liquid to evaporate, or more specifically, the force per unit area exerted by the vapor of the chemical in equilibrium with its solid or liquid form. For example, gasoline placed in a sealed container will evaporate and diffuse throughout the headspace until an equilibrium is reached. The gasoline vapor in the headspace exerts a pressure on the container. The pressure within the headspace can be measured, usually as millimeters of mercury (mm Hg) or inches of water, in a manometer connected to the headspace. Vapor pressure increases strongly with increasing temperature. Vapor pressure is applicable when NAPL is present. Vapor pressure  $P_v$  (Pa) can be converted to vapor density or concentration  $C_v$  ( $\text{g m}^{-3}$ ) with the Ideal Gas Law

$$C_v = MP_v / RT \quad (2-1)$$

with molecular weight  $M$  ( $\text{g mol}^{-1}$ ), universal gas constant  $R$  ( $8.314 \text{ Pa m}^3 \text{ mol}^{-1} \text{ K}^{-1}$ ), and temperature  $T$  (K).

(2) Raoult's law provides an approximation of the vapor pressures of compounds over a NAPL mixture such as a petroleum product. Raoult's law states that the partial vapor pressure  $P_{vi}$  of a constituent  $i$  in a gaseous mixture is equal to the mole fraction  $X_i$  of constituent  $i$  in the NAPL, times the vapor pressure  $P_i^\circ$  of the pure constituent  $i$  (which is a function of temperature):

$$P_{vi} = X_i P_i^\circ \quad (2-2)$$

(3) Henry's law determines the extent of volatilization of a contaminant dissolved in water. The Henry's constant  $K_H$  expresses the ratio of the compound's concentration in the vapor phase  $C_v$  (mass/volume air) to the compound's concentration in the liquid phase  $C_l$  (mass/ volume of liquid), at equilibrium

$$K_H = C_v/C_l \quad (2-3)$$

The ratio is therefore defined as mass per unit of vapor divided by mass per unit of liquid, or equivalently, mole fraction in the vapor phase divided by mole fraction in the liquid phase. In either case, Henry's law constant is not truly dimensionless. Care must be exercised with Henry's constants because they can be given as  $K_H$  above, or as  $k_H$  in units such as atm-ml/gram or, more commonly, atm·m<sup>3</sup>/mole. The Henry's constant for a given compound increases strongly with increasing temperature.

(4) Boiling point indicates the temperature at which a compound's vapor pressure equals the vapor pressure of the atmosphere, which at sea level is approximately 760 mm Hg. Atmospheric pressure, and thus boiling point, decreases significantly with increasing elevation above sea level. Inducing a vacuum in soil causes the pressure in the air-filled soil pores to decrease, leading in turn to a lowering of the boiling point and an increase in volatilization of the contaminant.

(5) Soil distribution coefficient ( $K_d$ ) indicates the tendency of a compound in solution to adsorb to the surface of particles of soil or organic matter. At equilibrium, a nonpolar organic compound is thus seen to distribute itself between solution concentration  $C_w$  and sorbed concentration  $C_s$ , as a function of their ratio:  $K_d = C_s/C_w$ , with  $K_d$  being equal to the soil sorption or partition coefficient. The value of  $K_d$  for a given organic compound is not constant, however, but tends to increase linearly for soils with increasing organic carbon (OC) and clay contents. The slope of the relationship between  $K_d$  and % organic C is the amount of sorption on a unit carbon content basis ( $K_{oc}$ ) (Hassett and Banwart 1989) in which  $K_{oc} = K_d/f_{oc}$  (where  $f_{oc}$  is the fraction of organic content in the soil). Thus  $K_{oc}$  values may be viewed as sorption coefficients normalized to organic carbon content.

(6)  $K_{oc}$  values are not often readily available, and octanol-water partition coefficients ( $K_{ow}$ ), which are highly correlated with  $K_{oc}$  values, are commonly used as indicators of the tendency for adsorption.  $K_{ow}$  is the equilibrium ratio of the contaminant concentration in *n*-octanol to the contaminant concentration in distilled water. There are numerous equations that have been empirically developed relating  $K_{ow}$  to  $K_{oc}$  (Dragun 1988). If the  $K_{ow}$  of a constituent of concern is known, its  $K_{oc}$  can be calculated and then its soil adsorption coefficient ( $K_d$ ) can be estimated by multiplying the  $K_{oc}$  by the  $f_{oc}$ .

(7) Although soil adsorption coefficients imply equilibrium and reversible sorption, soil/fluid/vapor partitioning processes are often neither in equilibrium nor reversible and are, therefore, not well predicted by soil adsorption coefficients. Two-compartment sorption models are hypothesized to explain this behavior wherein sorbed compounds may not desorb as readily as predicted because, over time, they can become more strongly associated within less accessible sorption sites or more resistant soil fractions. Release of compounds from dead-end micropores is similarly recognized to be diffusion-limited (Scow, Simkins, and Alexander 1986; Pignatello 1989). Thus, compounds may not be as susceptible to volatilization or leaching or as bioavailable as would be expected if their fate was not desorption limited. As a consequence, compounds can prove to be more persistent during treatment than would otherwise be expected.

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(8) Solubility determines the degree to which a contaminant dissolves into groundwater and unsaturated zone pore water. Compounds with high solubility are usually more mobile in infiltrating precipitation and groundwater and are also generally more biodegradable than less soluble compounds.

(9) The biodegradability of contaminants vary substantially even among compounds of the same class, such as petroleum hydrocarbon. Factors such as solubility, temperature, oxygen availability, pH, and presence of toxicants affect the biodegradation kinetics of contaminants. Biodegradation kinetics may significantly affect the rate of site remediation by SVE/BV.

*c. Soil properties.* Like contaminant physical and chemical properties, porous medium and fluid characteristics strongly influence contaminant fate and transport.

(1) Texture describes the size range of particles in the soil. A textural characterization can be either qualitative, as when a soil is broadly referred to as sandy or clayey, or quantitative, as when the distribution of particle sizes is measured by a mechanical analysis. In the latter case, textural classifications can be applied using standardized systems (e.g., U.S. Department of Agriculture (USDA) system; ASTM Unified Soil Classification System). The distribution of pore sizes in the subsurface is ultimately more important to considerations of SVE/BV than is the distribution of particle sizes, because it is through the pores that fluid flow occurs. A relationship exists between pore size and particle size with coarser grained soils generally having larger pore spaces and fine-grained soils generally having smaller pore sizes.

(2) Porosity ( $n$ ) is the (dimensionless) ratio of the void volume ( $V_v$ ) to the total volume ( $V_t$ ) of the porous medium, usually expressed as a decimal fraction or percent. Soil pores can be occupied by vapor, water, and/or NAPL. Porosity can be calculated from the bulk density of the soil ( $\rho_b$ ) which is the dry weight of soil per bulk volume (i.e., of both soil and pore space) by

$$n = 1 - (\rho_b / \rho_s) \quad (2-4)$$

with particle density  $\rho_s$ . For many inorganic soil particles,  $\rho_s$  is approximately equal to 2.65 g/cm<sup>3</sup>. Air-filled porosity is designated  $n_a$ . Geotechnical engineers typically term  $\rho_b$  the dry density.

(3) Saturation ( $S$ ) is the volume of a fluid per volume of soil pore space  $V_{\text{pores}}$ . When expressed as a percentage, it is termed "degree of water saturation",  $S_w$  (dimensionless), i.e.  $S_w = V_w / V_{\text{pores}}$ . Moisture content, by contrast, is the amount, by weight or volume, of liquid water in a soil. When expressed on a mass basis, moisture content  $w$  is the mass of water ( $M_w$ ) in a soil sample divided by its oven-dry mass ( $M_{\text{soil}}$ ),  $w = M_w / M_{\text{soil}}$ . When expressed on a volume basis, moisture content  $\theta$  is the volume of water ( $V_w$ ) in a sample divided by the total bulk volume ( $V_t$ ) of the sample,  $\theta = V_w / V_t$ . Thus,  $S_w = \theta / n$ . To obtain volumetric moisture content from gravimetric moisture content, use the relation  $\theta = w \rho_b / \rho_w$ , where  $\rho_w$  is the density of water. Moisture content reduces the air-filled porosity of a soil and the number of air pathways. Air permeability is greater at lower moisture contents because a larger percentage of the pore space is available for vapor transport. In SVE, however, it is desirable to have some moisture content in the soil because desorption of contaminants from soil increases if films of water are present to displace contaminant molecules (USEPA 1991d). BV systems require at least 50 percent field capacity (preferably 75 to 80 percent of field capacity) to function optimally. Field capacity can be determined by saturating undisturbed soil samples, allowing the free water to drain and then measuring the moisture content. Field capacity is

the mass of water in the sample divided by the dry weight after allowing a saturated soil to drain for 24 hours. Because field capacity is a frequently misunderstood term, discussions of the concept and methods of measurement/prediction should be consulted (Hillel 1980b; Cassel and Nielsen 1986). Table 4-8 of this document provides some typical field capacity values for 12 types of soil.

(4) Wetting and nonwetting phases. In a porous medium containing two fluid phases (e.g., water and air), the wetting phase is the fluid that occupies positions closest to points of contact between solid phase particles, while the nonwetting phase is the fluid that occupies positions more removed from interparticle contact points. For the case in which the soil pores are occupied either by water or air, water is usually considered the wetting phase and air the nonwetting phase. The nonwetting (i.e., air) phase saturation  $S_{nwa}$  is then defined as  $1 - S_w$ , where  $S_w$  is the degree of water saturation. When another nonwetting phase such as oil is also present, it is considered nonwetting with respect to water and wetting with respect to air, and its saturation  $S_{now}$  can be defined such that  $S_w + S_{nwa} + S_{now} = 1$ .

(5) Residual water saturation  $S_r$  is the volume fraction of immobile water. Such water occupies disconnected pores and cannot flow because it is held in place by capillary forces. Capillary forces are intrinsically greater in finer-grained soils, due to the smaller pore (or capillary) sizes. Accordingly, the residual water saturation in clay and silt layers will tend to be higher than in adjacent sand and gravel layers. This tends to accentuate the lithologic influence on air permeability.

(6) Residual NAPL saturation  $S_{ro}$  is the degree of NAPL saturation which remains in a soil that, having contained NAPL, is subjected to drainage until the NAPL- filled pore spaces are discontinuous. Residual NAPL saturation varies with soil type, NAPL type, and moisture content. Ganglia are isolated globules of NAPL that may collect in subsurface pools, cracks, or fissures.

(7) Capillary pressure  $P_c$  between two phases (e.g., air and water or oil and water) is defined as

$$P_c = P_n - P_w \quad (2-5)$$

where  $P_n$  and  $P_w$  are the nonwetting and wetting phase pressures [ $ML^{-1}T^{-2}$ ], respectively (N.B: the use of square brackets indicates dimensions, with M = mass; L = length; and T = time.). Capillary pressure can be expressed in terms of pressure head  $h_c$ , (also known as capillary pressure head or simply capillary head) by observing that under hydrostatic conditions,  $h = P/\rho g$ , with  $h$  = pressure head [L];  $\rho$  = density [ $M L^{-3}$ ]; and  $g$  = acceleration of gravity [ $L T^{-2}$ ]. Thus, dividing Equation 2-5 through by  $\rho$  and  $g$ ,

$$h_c = h_n - h_w \quad (2-6)$$

where  $h_n$  and  $h_w$  are the nonwetting and wetting phase pressure heads, respectively. In unsaturated porous media, capillary pressures are less than atmospheric pressure. Since a liquid in equilibrium with atmospheric pressure is, by convention, assigned a pressure head value of zero, unsaturated soils that contain air-filled pores connected to the atmosphere have liquid-phase pressure heads that are less than zero, i.e., negative. In air-water systems, such negative heads are often expressed as positive values of capillary pressure head (also known as tension head, matric suction, or simply suction,  $\psi$ ) (Hillel 1980a), i.e.,  $h_c = -\psi$ . By contrast, pressures are sometimes expressed in terms of absolute pressure relative to a reference pressure of zero in an absolute vacuum. Table 2-1 summarizes typical conversions among various units of pressure and pressure head.

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**Table 2-1 Pressure/Pressure Head Conversions**

| Units of Pressure |                              |
|-------------------|------------------------------|
| 1 bar=            | $10^5 \text{ N m}^{-2}$      |
| =                 | 0.987 atmospheres            |
| =                 | 14.5 psi                     |
| =                 | $10^6 \text{ dynes cm}^{-2}$ |
| =                 | 100 kPa                      |

| Units of Pressure Head |                         |
|------------------------|-------------------------|
| and is equivalent to:  | 1033 cm column of water |
|                        | 75.99 cm column of Hg   |

**Example:**

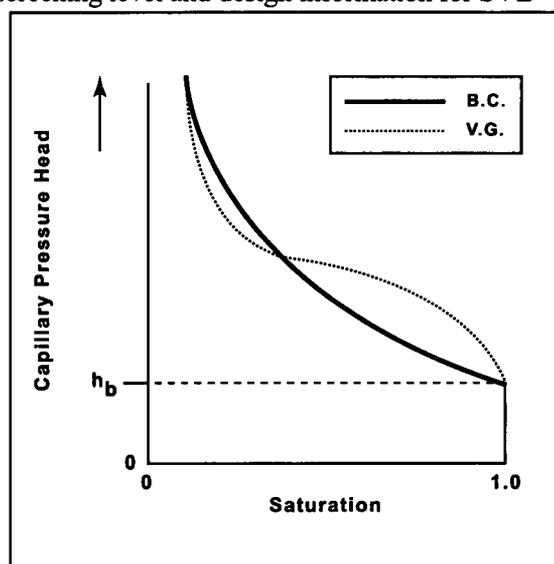
A vacuum gauge mounted on the wellhead of a vent well reads in cm H<sub>2</sub>O (gauge). In other words, it reads 0 cm H<sub>2</sub>O when the air in the well is at atmospheric pressure. When a blower is turned on and exerts a vacuum on the well, the gauge reads a vacuum head of 100 cm H<sub>2</sub>O, which is equivalent to a vacuum head of 7.35 cm Hg.

$$\text{i.e., } \frac{100 \text{ cm H}_2\text{O}}{1020 \text{ cm H}_2\text{O}} = \frac{7.35 \text{ cm Hg}}{75.01 \text{ cm Hg}} = \frac{9.8 \text{ kPa}}{100 \text{ kPa}}$$

These can also be expressed as gauge pressure heads of -100 cm H<sub>2</sub>O or -7.35 cm Hg, or as a gauge pressure of -9.8 kPa.

The readings can, if desired, be converted to absolute pressures/pressure heads, as follows: Atmospheric pressure plus gauge pressure equals absolute pressure. Therefore, if barometric pressure = 101.32 kPa, absolute pressure = 101.32 kPa + (-9.8 kPa) = 91.52 kPa. An equivalent absolute pressure head is 76.0 cm Hg + (-7.35 cm Hg) = 68.65 cm Hg.

(8) Capillary pressure head-saturation curves (also known as moisture retention curves, soil moisture characteristic curves, or  $h_c(S)$  curves) can provide useful screening level and design information for SVE and BV. Not only do such curves reflect the pore-size distribution of the soil, they also reveal the energy associated with soil water at various levels of saturation (Figure 2-4). As water saturation declines, the remaining water is held more and more tenaciously within smaller and smaller soil pores, and increasingly more energy per unit weight of water (i.e., head) is required to extract it. Upon the imposition of a vacuum on an SVE well in a formation that includes lenses of soil or zones that are initially saturated, the largest pores empty of water first, at the *air entry suction* (also known as the *bubbling pressure head*,  $h_b$ ), followed by incrementally smaller pores as smaller values of capillary pressure head (i.e., larger suctions) are applied by the vacuum. The onset of air permeability in an initially saturated porous medium, corresponding to the air entry value, occurs when the gaseous phase first occupies an interconnected network of air-filled pores. This air entry value,



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**Figure 2-4 Capillary pressure head-saturation curves exhibiting Brooks-Corey (B.C.) and Van Genuchten (V.G.) Analytical Functions**

which can be inferred from a capillary pressure head-saturation curve, gives an indication of the vacuums that will need to be exerted on a wet soil to implement SVE/BV. The "B.C." curve illustrated in Figure 2-4 has the shape of a Brooks-Corey analytical function, (Brooks and Corey 1966), and is most appropriate to represent soils exhibiting sharp air entry suctions. Soils that do not exhibit such behavior may be better represented by a Van Genuchten (1980) analytical function, as depicted by the "V.G." curve in Figure 2-4.

(9) Permeability or intrinsic permeability ( $k$ ) is a measure of the ease with which a porous medium can transmit air, water, or other fluid. Intrinsic permeability is a function only of the porous medium and has dimensions of length squared [ $L^2$ ]. Permeability may also be expressed in units of darcies: 1  $cm^2$  is approximately equivalent to  $10^8$  darcies. When permeability is expressed as a fraction of the maximum permeability value that the medium can exhibit for a given fluid, it is termed *relative permeability*,  $k_r$  (dimensionless).

(10) Hydraulic conductivity ( $K$ ) is a measure of the ease with which a porous medium can transmit a specific fluid, usually water. Hydraulic conductivity is a function of both the porous medium and the fluid, and has dimensions [ $L T^{-1}$ ]. When hydraulic conductivity is determined under water-saturated conditions, it is known as the saturated hydraulic conductivity ( $K_s$ ). Intrinsic permeability is related to saturated hydraulic conductivity as follows:

$$k = K_s \mu_w / \rho_w g \quad (2-7)$$

where  $\mu_w$  is the dynamic viscosity of water [ $M L^{-1} T^{-1}$ ] and  $\rho_w$  is the density of water [ $M L^{-3}$ ]. For water at approximately 293 K,  $k = (10^{-7} \text{ m-sec})(K_s)$ , where  $k$  is expressed in units of  $m^2$  and  $K_s$  in  $m\text{Asec}^{-1}$ , or  $k = (10^{-5} \text{ cm-sec})(K_s)$  where  $k$  is expressed in units of  $cm^2$  and  $K_s$  in  $cm \text{ sec}^{-1}$ .

(11) Air permeability ( $k_a$ ) is the ability of vapors to flow through the porous medium. It is a property of the porous medium only and has dimensions [ $L^2$ ]. Relative air permeability  $k_{ra}$  expresses air permeability as a (dimensionless) fraction of intrinsic permeability,  $k_{ra} = k_a/k$ . Air permeability is perhaps the most important soil parameter with respect to the success and design of SVE/BV systems. Air prefers to flow through zones of higher air permeability (i.e., paths of least resistance), and the air permeability of the subsurface should be well characterized before implementing SVE or BV. Because air-filled porosity determines the pore volume available for vapor transport, air permeability is a function of saturation. As the degree of water saturation decreases, and as air-filled porosity increases accordingly, the relative permeability of the soil to air increases as a steeply nonlinear function of the degree of saturation.

(a) Models are available for predicting the dependence of relative permeability on saturation, given measured capillary pressure head-saturation data for a soil. Brooks and Corey (1966) developed analytic functions relating capillary pressure head to saturation that can be fit to measured  $h(S)$  data, and used to predict the dependence of relative air permeability on saturation,  $k_{ra}(S)$ , which is essential for modeling airflow under partially saturated conditions.

(b) The air permeability is significantly influenced by the density and viscosity of the soil gas, both of which are, in turn, a function of temperature. Over the range of temperatures commonly encountered in SVE/BV (280K-295K), density and viscosity will not be affected significantly by changes in temperature. With thermal enhancements, however, such changes can become considerable.

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(12) Peclet number is a dimensionless number that relates the effectiveness of mass transfer by advection to the effectiveness of mass transfer by diffusion. Peclet numbers have the general form of  $vd/D$  where  $v$  is the velocity,  $d$  is the characteristic length scale, which in this case is the average grain size, and  $D$  is the diffusion coefficient of the contaminant in air. For mass transfer parallel to the direction of advective flow, diffusion is dominant at Peclet numbers less than 0.02, and advection is dominant at Peclet numbers greater than 6. For mass transfer perpendicular to advective flow, diffusion dominates at Peclet numbers less than 1, and advection dominates at Peclet numbers greater than 100 (Gillham and Cherry 1982).

(13) Humidity is important in SVE and BV. Water vapor, like liquid water, promotes desorption of contaminants from soil particles. As relative humidity approaches 100 percent, however, liquid water will condense in cooler system components and can, for example, reduce the efficiency of offgas treatment.

## 2-4. Fundamentals of Vapor Flow in Porous Media

Sites can be modeled to approximate the performance of a SVE/BV system, and to explore design alternatives. Models, however, have to make some simplifying assumptions to represent the site mathematically. In many cases these simplifying assumptions do not affect the final result, but the possibility that they could should be kept in mind. Some of these assumptions may include homogeneous, isotropic conditions, while sites are frequently heterogeneous (e.g., layered) and directionally dependent in their properties. In addition, models are always dependent on the representativeness of the data to the actual site conditions. These considerations are key to understanding the extent to which the model can be expected to accurately predict site performance.

*a. Darcy's law for vapor flow.* Laminar flow in porous media is generally described by Darcy's law, an empirical relationship of the form

$$q = \frac{k_i \rho g}{\mu} \nabla H \quad (2-8)$$

where

$q$  = discharge per unit area [L/T]

$k_i$  = intrinsic permeability [ $L^2$ ]

$\rho$  = fluid density [ $M/L^3$ ]

$g$  = acceleration of gravity [ $L/T^2$ ]

$\mu$  = dynamic fluid viscosity [ $M/L-T$ ]

$\nabla$  = gradient operator [ $L^{-1}$ ]

$H = \text{total head [L]}^*$

\*Note that a value for pressure can be obtained by multiplying head by  $\rho g$ .

(1) As described in paragraph 2-3c(9), intrinsic permeability  $k$  is a property of the porous medium. Density  $\rho$  and viscosity  $\mu$  are properties of the particular fluid under consideration. Values of viscosity of air at normal temperature and pressure (NTP) are  $1.83 \times 10^{-5}$  newton-s  $\text{m}^{-2}$ . This is equivalent to  $1.83 \times 10^{-4}$  gm  $\text{cm}^{-1} \text{s}^{-1}$  and  $1.83 \times 10^{-2}$  centipoise. Likewise, values of density of air at NTP are  $1.20 \times 10^{-3}$  Mgm  $\text{m}^{-3}$ , equivalent to  $1.20 \times 10^{-3}$  gm  $\text{cm}^{-3}$  and  $7.49 \times 10^{-2}$  lb  $\text{ft}^{-3}$ . NTP is a gas industry reference, with normal temperature defined as  $21.1^\circ \text{C}$  ( $70^\circ \text{F}$ ) and normal pressure as 1 atmosphere (101.35 KPa or 14.6960 psia).

(2) Head  $H$  (energy per unit weight) [L] can be expressed equivalently as pressure  $P$  (energy per unit volume) [ $\text{ML}^{-1}\text{T}^{-2}$ ] and as potential  $\phi$  (energy per unit mass) [ $\text{L}^2\text{T}^{-2}$ ]. To convert head to pressure, multiply head by  $\rho g$ , where  $\rho$  is the density of the fluid and  $g$  the acceleration of gravity. To convert head to potential, multiply head by  $g$ . Finally, to convert pressure to potential, divide pressure by  $\rho$  (Hillel 1980a).

(3) Total fluid potential  $\phi$  (i.e., mechanical energy per unit mass) [ $\text{L}^2\text{T}^{-2}$ ] is defined by Bernoulli's equation:

$$\phi = gz + \frac{v^2}{2} + \int_{P_0}^P \frac{1}{\rho} dP \quad (2-9)$$

where

$z = \text{elevation [L]}$

$v = \text{fluid velocity [L/T]}$

$P = \text{absolute pressure [M/LT}^2\text{]}$

(a) The first term of Equation 2-9 is gravitational potential, the second term is inertial potential, and the third term is pressure potential. For vapor flow, gravitational effects are small for the elevation differences under consideration. Likewise, inertial effects can be neglected for laminar flow. As a result, the gradient of total fluid potential  $\phi$  becomes

$$\nabla\phi = \frac{1}{\rho} \nabla P \quad (2-10)$$

and Darcy's law for vapor flow is

$$q = \frac{k_a}{\mu} \nabla P \quad (2-11)$$

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(b) Note that intrinsic permeability  $k_i$  has been replaced by air permeability  $k_a$  in Equation 2-11. Whereas intrinsic permeability is a measure of the resistance to flow through the total pore space, air permeability represents the resistance to flow through only the air-filled pore space. Since the air-filled porosity deviates from the total porosity by the amount of water saturation, air permeability generally is lower than intrinsic permeability (paragraph 2-3c).

(4) Klinkenberg (1941) showed that for clayey materials, gas slippage occurs, resulting in higher flow rates than those predicted by Darcy's law. Gas slippage, commonly referred to as the Klinkenberg effect, results from nonzero flow velocities along pore walls. Massmann (1989) indicates that, for pore radii greater than approximately  $10^{-3}$  mm, the effects of slip flow are small relative to viscous flow and can be neglected. As described below, McWhorter (1990) has developed an exact solution for radial flow incorporating gas slippage.

*b. Partial differential equation for vapor flow.* The partial differential equation for vapor flow is developed by combining Darcy's law with the principle of conservation of mass. Conservation of mass, for a compressible fluid, states that

$$\nabla \cdot (\rho q) = \frac{\partial(\rho n_a)}{\partial t} \quad (2-12)$$

where

$n_a$  = air-filled porosity

Substituting Darcy's law into Equation 2-12 yields:

$$\nabla \cdot \left( \rho \frac{k_a}{\mu} \nabla P \right) = \frac{\partial(\rho n_a)}{\partial t} \quad (2-13)$$

Expressing vapor density in terms of pressure using the ideal gas law (Equation 2-1), and treating porosity and viscosity as constants, Equation 2-13 reduces to

$$\nabla \cdot (k_a \nabla P^2) = 2 n_a \mu \frac{\partial P}{\partial t} \quad (2-14)$$

(1) This is a nonlinear partial differential equation with few exact solutions. The primary source of nonlinearity in SVE/BV applications is the dependence of gas density upon pressure (McWhorter 1990). Other sources of nonlinearity include pressure-dependent viscosity, gas slippage, and nonlaminar flow. Nonlaminar flow occurs under high pressure gradients (such as in petroleum reservoirs), whereas gas slippage typically occurs only in clayey soils.

*c. Steady state vapor flow.*

(1) Since most SVE/BV systems are designed for long-term operation, steady-state flow models are appropriate for system design. Steady-state solutions can be used for air permeability tests, provided that

sufficient time is allowed for flow to stabilize. For the case of one-dimensional radial flow, steady-state solutions can also be used to analyze transient permeability test data, for a condition known as the pseudo-steady state (paragraph 2-4e). This method incorporates pressure-dependent density, which is not possible using the more common transient analysis methods (e.g., Johnson, Kemblowski, and Colthart (1990b)).

(2) The partial differential equation for steady-state flow is obtained by setting the right-hand side of Equation 2-14 equal to zero

$$\nabla \cdot (k_a \nabla P^2) = 0 \quad (2-15)$$

(3) For isotropic conditions,  $k_a$  is independent of  $\nabla^2 P^2$ , and

$$\nabla^2 P^2 = 0 \quad (2-16)$$

(4) Equation 2-16 is equivalent to Laplace's equation in  $P^2$ . Laplace's equation is a classical partial differential equation that is used to solve problems involving potential flow. Functions that satisfy Laplace's equation include both stream functions and potential functions.

(5) Equation 2-16 can be solved using analytical or numerical methods. Analytical methods involve finding closed-form integrals that satisfy Equation 2-16. Numerical methods involve discretizing the flow domain into a grid, and solving Equation 2-16 using iterative techniques. Numerical methods can be used to evaluate heterogeneous systems with irregular geometries, whereas analytical methods are better suited for homogeneous systems with idealized geometries. However, permeability tests are most commonly analyzed using analytical solutions. Since these solutions illustrate the general principles of flow, the following development is based on analytical methods.

(6) For linear flow in the one dimension, Equation 2-16 is

$$\frac{d^2 P^2}{d x^2} = 0 \quad (2-17)$$

where

$x$  = the one-dimensional cartesian coordinate [L]

For horizontal flow to a long, fully penetrating trench, with  $P = P_{atm}$  at  $x = L$ , the solution to Equation 2-17 is:

$$P^2 - P_{atm}^2 = \frac{2 Q_l P^* \mu}{b k_a} (L - x) \quad (2-18)$$

where

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$Q_l$  = volumetric flow rate per unit length of trench [ $L^2/T$ ]

$P^*$  = absolute pressure at the point of flow measurement [ $M/LT^2$ ]

$b$  = thickness of the vadose zone [ $L$ ]

This equation can be used to calculate the lateral pressure distribution near a long trench, for a vadose zone with upper and lower impermeable boundaries. Alternatively, it can be used to determine the required spacing between alternating extraction and passive inlet trenches, where  $L$  is the distance between trenches.

(7) For radial flow in one dimension, Equation 2-16 is

$$\frac{d^2 P^2}{dr^2} + \frac{1}{r} \frac{dP^2}{dr} = 0 \quad (2-19)$$

where

$r$  = the one-dimensional radial coordinate (equivalent to  $[x^2 + y^2]^{1/2}$  in cartesian coordinates)

The solution to this equation for horizontal flow to a line sink at  $r = 0$ , with  $P = P_i$  at  $r = r_i$  is

$$P^2 - P_i^2 = \frac{Q_v P^* \mu}{\pi b k_a} \ln\left(\frac{r_i}{r}\right) \quad (2-20a)$$

or, if  $Q_v > 0$  (i.e., if the extraction flow rate is considered positive)

$$P^2 - P_i^2 = \frac{Q_v P^* \mu}{\pi b k_a} \ln\left(\frac{r}{r_i}\right) \quad (2-20b)$$

where

$Q_v$  = volumetric flow rate [ $L^3/T$ ]

(8) Equation 2-20 can be used to estimate  $k_a$  based on field measurements at a tightly covered or highly anisotropic (vertical permeability much smaller than horizontal permeability) site, such as during a pilot test, by measuring  $P_i$  while extracting at constant  $Q_v$ . If  $k_a$  is known at a tightly covered or anisotropic site, then equation 2-20 can be used to estimate the pressure distribution surrounding an extraction well at steady state.

(9) By extrapolating equation 2-20 to the radius at which  $P = P_{atm}$ , the radius of pressure influence ( $r_e$ ) can be determined. In a practical sense,  $r_e$  is the limit of measurable pressure influence resulting from an extraction well. The radius of pressure influence may be obtained by fitting data from multiple observation

points to Equation 2-20, or it can be obtained by preparing a semilog plot of pressure versus distance (Figure 2-5). This type of plot often termed a distance-drawdown graph (Driscoll 1986).

(10) However, the radius of pressure influence,  $r_e$ , is both somewhat problematic, and misunderstood.

(a) Mass balance dictates that for continuous withdrawal of air from a stratum with impermeable upper and lower boundaries,  $r_e$  must increase with time. This conclusion is borne out by analyses of transient

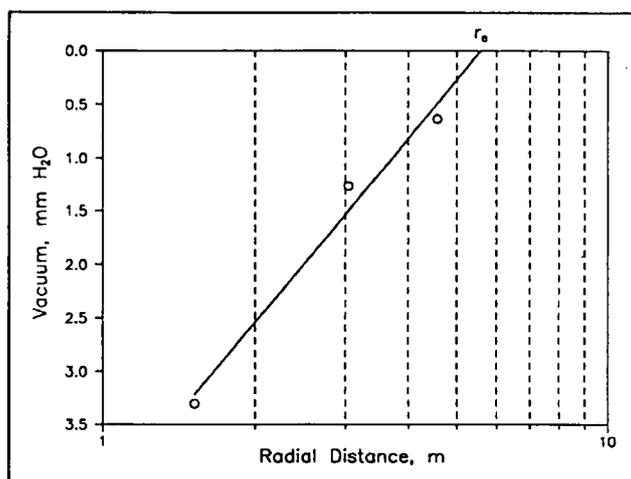


Figure 2-5 Use of distance-drawdown graphs to determine  $r_e$ .

radial flow, which indicate that  $r_e$  increases in proportion to the square root of time (McWhorter and Sunada 1977; McWhorter 1990). However, the widespread acceptance of a fixed  $r_e$  reflects the common field observation that the limit of radial pressure influence often shows little change over time. This phenomenon may be explained by leakage of air through upper and lower boundaries, attesting to the rarity of truly horizontal flow. As mentioned above, the widespread observation that  $r_e$  often shows little change over time attests to the rarity of one-dimensional radial flow. Beckett and Huntley (1994) conclude that even where the ground surface is paved, vertical leakage is the rule, rather than the exception. Vertical leakage results in

two-dimensional radial flow.

Historically,  $r_e$  has been used as the basis of design for extraction well networks. Designers have interpreted the zone of vacuum influence around a well as also corresponding to the "capture zone" of the extraction well. By subsequently selecting an arbitrary distance within this zone of vacuum influence (e.g., the radius at which the vacuum equals 0.25 cm water vacuum), designers have established well spacings for SVE well networks. Unfortunately, this is a completely inappropriate interpretation of this phenomenon. As described further in Chapter 5, SVE designs should be based on pore gas velocities or the rates of pore gas exchange, which, are a function of both the pressure (vacuum) distribution around the extraction point and the associated soil air permeability. Thus, using Figure 2-5 directly for SVE design purposes is not appropriate.

(11) An analytical solution for two-dimensional flow to a well can be obtained by superposition of a point sink solution along the length of the well screen. Equation 2-16 for two-dimensional radial flow is:

$$\frac{\partial^2 P^2}{\partial r^2} + \frac{1}{r} \frac{\partial P^2}{\partial r} + \frac{\partial^2 P^2}{\partial z^2} = 0 \quad (2-21)$$

where

$r$  = the horizontal radial coordinate (equivalent to  $[x^2 + y^2]^{1/2}$  in cartesian coordinates)

$z$  = the vertical radial coordinate (equivalent to the vertical cartesian coordinate)

The solution to this equation for a point sink located at  $r = 0, z = z'$  in an infinite space, is

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2 \pi k_a} \frac{l}{\sqrt{r^2 + (z - z')^2}} \quad (2-22)$$

where

$z'$  =  $z$ -coordinate of the point sink

The point sink solution can be integrated with respect to  $z$  to obtain a line sink solution in an infinite space

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2 \pi k_a (L - l)} \ln \left\{ \frac{z - l + \sqrt{r^2 + (z - l)^2}}{z - L + \sqrt{r^2 + (z - L)^2}} \right\} \quad (2-23)$$

where

$l$  =  $z$ -coordinate of the top of the well screen

$L$  =  $z$ -coordinate of the bottom of the well screen

The limitation to this analytical solution is that accounting for the effects of atmospheric and impermeable boundaries typically requires the summation of a large number of additional terms. A solution for two-dimensional flow to a well in a vertically bounded aquifer can be found using the method of images presented in Appendix E. The solution is sufficiently complex, however, that there is little advantage to using the analytical form over one of the widely available numerical model tools listed in Appendix C. A graphical method for predicting pressure distribution around an extraction or injection well is provided by Shan and others (1992). The methodology described in this paper is a valuable tool for the system designer.

(12) Travel time is useful in SVE/BV design for determining the required flow rates and well spacings necessary to achieve a desired air exchange rate. Travel time can be obtained by integrating the reciprocal of the seepage velocity along a streamline (path of flow):

$$t = \int \left( \frac{l}{q_s} \right) ds \quad (2-24)$$

where

$s$  = distance along a streamline, and

$q_s$  = seepage velocity

The seepage velocity can be obtained from Darcy's Law:

$$q_s = \frac{k_a}{n_a \mu} \nabla P \quad (2-25)$$

and the gradient of pressure can be obtained from the appropriate steady-state flow equation.

Assuming incompressible flow, the gradient of pressure for one-dimensional radial flow is:

$$\frac{dP}{dr} = \frac{Q_v \mu}{2 \pi b k_a r} \quad (2-26)$$

which can be integrated using Equation 2-24 to obtain:

$$t = \frac{\pi r^2 b n_a}{Q_v} \quad (2-27)$$

Equation 2-27 is equivalent to the pore volume of a cylinder surrounding an extraction well, divided by the discharge of the well.

(a) For the flow of a compressible gas, the integration indicated by Equation 2-24 generally requires numerical techniques. Simple finite-difference algorithms may be used for linear or radial one-dimensional flow, whereas more sophisticated particle tracking routines may be used for two-dimensional or three-dimensional flow. Shan, Falta, and Javandel (1992) provide travel times from the ground surface to an extraction well for various well screen positions in a vadose zone with an upper atmospheric boundary and a lower impermeable boundary. The travel times are provided in dimensionless form, allowing application to a particular field problem through a simple scaling procedure.

(b) King (1968) also provides vertical travel times from an injection well to the ground surface in a vadose zone with an upper atmospheric boundary and a lower impermeable boundary. This represents the minimum travel time from an injection well to the ground surface. The vertical travel times are provided in dimensionless form for a variety of well screen positions.

*d. Transient vapor flow.* The partial differential equation for transient flow is

$$\nabla \cdot (k_a \nabla P^2) = 2 n_a \mu \frac{\partial P}{\partial t} \quad (2-28)$$

(1) McWhorter (1990) developed an exact solution to a more rigorous form of Equation 2-14 accounting for gas slippage and pressure dependent viscosity. McWhorter's solution applies for one-

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dimensional radial flow with upper and lower impermeable boundaries. A simplified case of McWhorter's solution is presented in Appendix D, for analysis of transient air permeability test data.

(2) Johnson, Kemblowski, and Colthart (1990b), following Muscat, (1931), proposed linearizing Equation 2-14 by expressing  $P^2$  as the product of atmospheric pressure  $P_{atm}$  and a deviation from that pressure  $P\rho$ . The resulting equation expressed in one-dimensional radial coordinates is

$$\nabla \cdot (\nabla P') = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P'}{\partial t} \quad (2-29)$$

(3) Equation 2-29 has the same form as the linearized Boussinesq equation for groundwater flow. This equation essentially treats air as an incompressible fluid.

(4) Massmann (1989) determined that the errors introduced by substituting  $P$  for  $P^2$  are negligible for vacuums less than 0.2 atmospheres, gauge. Accordingly, Massmann proposed that groundwater flow models based on the linearized Boussinesq equation can be applied to vapor flow, with the substitution of pressure head (i.e.,  $P/\rho g$ ) for hydraulic head, and soil gas conductivity for hydraulic conductivity. Model simulations should be limited to vacuums less than 0.2 atmospheres, gauge, i.e., in accord with the assumption of incompressible flow.

(5) In one-dimensional radial coordinates, Equation 2-29 is:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial P'}{\partial r} \right) = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P'}{\partial t} \quad (2-30)$$

The solution to this equation for a constant sink at  $r = 0$ , with  $P = P_{atm}$  at  $r = 4$ , is (Johnson et al. 1990b):

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a u} \int_0^{\infty} \frac{e^{-x}}{x} dx \quad (2-31)$$

where

$Q$  = volumetric flow rate [ $L^3 T^{-1}$ ]

$b$  = the thickness of the vadose zone or stratum of interest [ $L$ ], and

$$u = \frac{r^2 n_a \mu}{4 k_a P_{atm} t} \quad (2-32)$$

(a) The integral in Equation (2-31) is known as the Theis well function (Theis 1935), where  $x$  is a dummy variable of integration. The Theis well function is commonly used for analysis of groundwater pump test data in confined aquifers. Related well functions have also been developed for unconfined radial flow (Neuman 1975) and leaky radial flow (Hantush and Jacob 1955).

(b) The Theis solution is accomplished by combining distance and time into the Boltzmann variable,  $u$ . If  $u$  is sufficiently small, then the integral in Equation 2-31 can be approximated using the first two terms of a Taylor series expansion. Using this approximation, Equation 2-31 reduces to:

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} \left( \ln \frac{4 k_a P_{atm} t}{r^2 n_a \mu} - 0.5772 \right) \quad (2-33)$$

Equation 2-33 is commonly known as the Cooper-Jacob approximation. Note that the pressure drawdown ( $P - P_{atm}$ ) varies linearly with  $\ln(t)$ . This equation is commonly used for transient air permeability test analysis (Appendix D).

(c) Equations 2-31 through 2-33 are based on the assumption of horizontal radial flow, with upper and lower impermeable boundaries. Beckett and Huntley (1994) suggest that these conditions rarely occur, even where asphalt or concrete surface covers are present. The effect of vertical flow through a leaky surface cover can be simulated by adding a leakage term to the partial differential equation for radial flow:

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} - \frac{L \mu}{k_a \rho g b} = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P}{\partial t} \quad (2-34)$$

where  $L$  is the leakage rate.

(d) For incompressible flow through a surface cover of thickness  $b_v$  and vertical air permeability  $k_v$ , the leakage rate per unit area is:

$$L = \frac{k_v \rho g}{\mu} \frac{(P - P_{atm})}{b_v} \quad (2-35)$$

Substituting  $L$  into Equation 2-34 yields:

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} - \frac{k_v}{k_a} \frac{(P - P_{atm})}{b b_v} = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P}{\partial t} \quad (2-36)$$

Introducing a leakage factor  $B$ , defined by:

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$$B = \sqrt{\frac{k_a b_v b}{k_v}} \quad (2-37)$$

yields an equation similar to the leaky aquifer equation for groundwater flow (McWhorter and Sunada, 1977):

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} - \frac{P - P_{atm}}{B^2} = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P}{\partial t} \quad (2-38)$$

(e) Employing the Hantush-Jacob leaky aquifer solution, available in most groundwater hydraulics texts, the solution to this equation is:

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} W(u, \frac{r}{B}) \quad (2-39)$$

where  $W(u, r/B)$  is the leaky well function. For vapor flow, the Boltzmann variable  $u$  is defined in Equation 2-32.

(f) Beckett and Huntley (1994) found a superior fit of field permeability test data using the leaky well function than that using the Theis well function at five sites. They conclude that vertical air leakage is the rule, rather than the exception. They state that use of the Theis well function (Equation 2-31), including its Taylor series approximation (Equation 2-33), results in overestimation of the air permeability and the allowable vapor extraction rate, and underestimation of the time required to achieve site cleanup.

*e. The pseudo-steady state.* For one-dimensional radial flow, the Cooper-Jacob approximation (Equation 2-33) predicts that the pressure difference between any two radial distances (provided  $u \leq 0.01$ ) is

$$P_2 - P_1 = \frac{Q_v \mu}{4 \pi b k_a} \left( \ln \frac{4 k_a P_{atm} t}{r_1^2 n_a \mu} - \ln \frac{4 k_a P_{atm} t}{r_2^2 n_a \mu} \right) \quad (2-40)$$

for  $r_2 > r_1 > 0$  and  $(P_2 - P_1) < P_1$

If  $P_1$  and  $P_2$  are measured at the same time, then

$$P_2 - P_1 = \frac{Q_v \mu}{4 \pi b k_a} \left( \ln \frac{r_2}{r_1} \right) \quad (2-41)$$

(1) This is identical to the steady-state equation for radial *incompressible* flow. As pointed out by McWhorter and Sunada (1977), this indicates that although pressure may be changing with time, the time rate of change of  $P$  is independent of  $r$  (as long as  $u \leq 0.01$ ). That is, while pressure measurements may vary with time, the difference in pressures between any two points remains constant (Figure 2-6).

(2) The foregoing analysis demonstrates that transient test data from multiple observation points can be analyzed using equations for steady-state radial flow, provided that pressure measurements are recorded simultaneously. This type of analysis is referred to as the pseudo-steady state (McWhorter and Sunada 1977). Where applied vacuums or pressures exceed 0.2 atmospheres gauge, pseudo-steady state analyses may be more accurate than Theis or Cooper-Jacob type analyses, since the effects of pressure-dependent density can be accommodated using steady-state solutions.

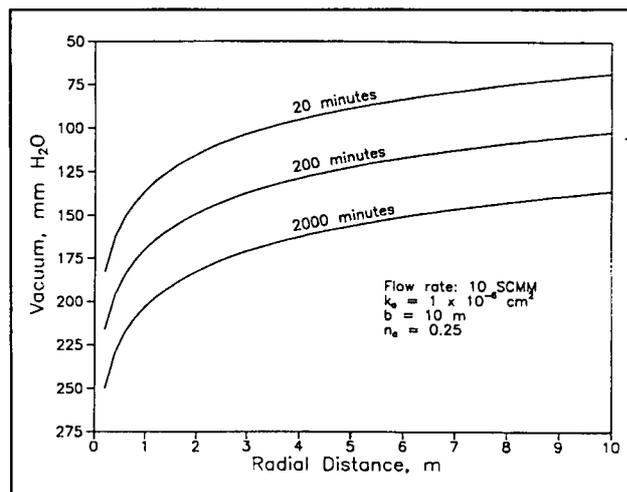


Figure 2-6 Transient pressure distributions calculated using the Cooper-Jacob approximation ( $\mu \leq 0.01$ )

## 2-5. Biodegradation Kinetics

a. *Fundamental principles.* Biodegradation can be expressed mathematically as a hyperbolic function, as in Michaelis-Menten kinetics equation:

$$R = -\frac{VC}{K+C} \quad (2-42)$$

with reaction rate  $R$ , maximum biodegradation velocity  $V$ , and biodegradation half-saturation constant  $K$ . The half-saturation constant is the contaminant concentration at which the biodegradation velocity is equal to half of its maximum value. The negative sign on the right-hand side indicates that the contaminant is

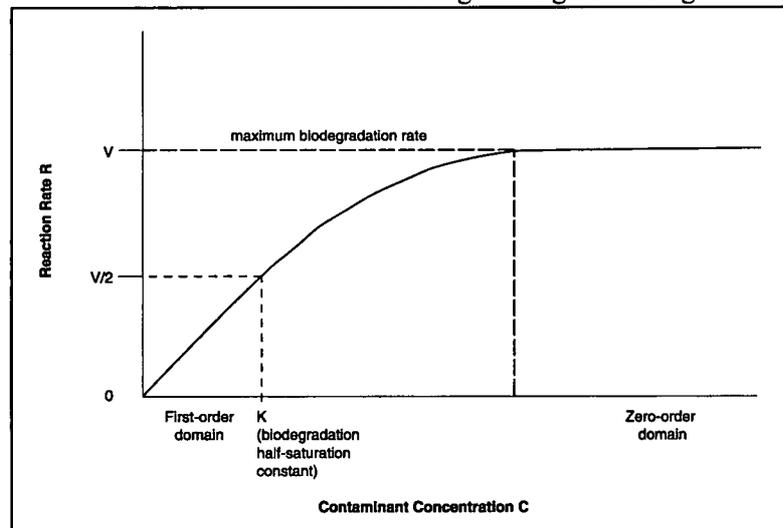


Figure 2-7 Biodegradation Reaction Rate as a Function of Substrate Concentration

being consumed. Reaction rate versus substrate concentration is sketched in Figure 2-7. Oxygen is assumed not to be limiting because abundant oxygen is provided to the unsaturated zone during BV. (This may often be an inappropriate assumption, see para 2-5a(6) below.)

(1) In equation 2-42, at high contaminant concentrations,  $K$  drops out and the  $C$ 's cancel. Biodegradation velocity is at its maximum,  $V$ , and biodegradation is zero order, i.e., the rate is independent of contaminant concentration

$$R = -V \quad (\text{when } K \ll C)$$

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(2) At low contaminant concentrations,  $R$  reduces to a first-order expression in which the biodegradation rate is equal to a first-order rate constant  $F$  ( $F = V/K$ ) times contaminant concentration

$$R = -FC \text{ (when } K \gg C) \quad (2-44)$$

(3) First-order kinetics are often appropriate in BV applications, in which case

$$C_t = C_o \exp(-Ft) \quad (2-45a)$$

$$\ln\left(\frac{C_t}{C_o}\right) = -Ft \quad (2-45b)$$

with initial concentration  $C_o$  and concentration at some later time  $C_t$ . If the first-order rate constant  $F$  is known, the time  $t$  required to achieve a treatment goal  $C_t$  can be estimated.

(4) The concept of half-life is derived from the latter equation. The half-life is the time required to degrade half of some initial contaminant concentration

$$\ln(0.05) = -Ft_{1/2} \quad (2-46a)$$

$$t_{1/2} = \frac{0.693}{F} \quad (2-46b)$$

(5) The first-order rate constant can be estimated from concentration versus time data, e.g., from microcosm or column studies. For example, if a reaction is first order, a semilog plot of Equation 2-45a gives a straight line whose slope is  $F$ . Kinetic parameters and half-lives are, of course, site-specific, depending on such factors as microbial population, moisture content, and availability of nutrients.

(6) It is critical to understand, however, that at many sites, contaminants are located both within the pores through which air flows, *and* in soil pores that only experience gas exchange through diffusive processes. Bacteria that must rely on diffusion to receive oxygen for aerobic biodegradation will have reaction rates that are also dependent on oxygen concentration. In these situations, equation 2-42 is no longer applicable, and the curve depicted in Figure 2-7 will be characteristically different. Indeed, oxygen uptake rates at many sites have been found to be first order with respect to oxygen, suggesting that oxygen diffusion, not contaminant concentration, controls contaminant removal rates. Therefore it is more practical to focus attention on oxygen respiration rather than on contaminant degradation kinetics. Oxygen concentrations are easily and directly measurable in the field, and may be related to contaminant removal through adoption of appropriate stoichiometric assumptions, as presented in paragraph 4-2g(4).

*b. Recent applications.* Few models of unsaturated zone biodegradation and BV have been developed. Jury et al. (1990) included first-order biodegradation in an analytical model of volatilization losses of subsurface VOC contamination. Corapcioglu and Baehr (1987) and Baehr and Corapcioglu (1987) developed a sophisticated one-dimensional finite difference model of unsteady multiphase multicomponent organic transport with static NAPL and air phases. The model assumed that biodegradation was limited by oxygen -- rather than substrate or nutrient -- availability.

(1) Bentley and Travis (1991) include biodegradation in a three-dimensional finite-difference model capable of simulating gas and liquid flow and multicomponent solute transport under saturated and unsaturated conditions. Michaelis-Menten kinetics are used for biodegradation, and BV situations are simulated.

(2) Ostendorf and Kampbell (1991) present an analytical model of unsaturated zone biodegradation of hydrocarbon vapors under natural (unvented) conditions. Gaseous diffusion is balanced against biodegradation. Oxygen and hydrocarbon vapors are modeled and related stoichiometrically as coupled constituents. Biodegradation is not simplified as zero or first order (Equation 2-28 was used). The model is fit to field probe cluster data (i.e., oxygen and total combustible hydrocarbon concentrations) by optimizing values of  $V$  and  $K$ .

(3) Ostendorf and Kampbell (1990) present an analytical BV model which balances storage, linear sorption, vertical advection, and Michaelis-Menten kinetics (Equation 2-42). No residual contamination is present in the unsaturated zone modeled. The model is tested against laboratory microcosm and field data. Good agreement endorsed both the simple modeling approach and the use of microcosms to predict field kinetics. The model is also used to simulate remediation times at a BV site.

(4) The Ostendorf and Kampbell (1990) paper also derives a microcosm model, which is an unsteady balance of linear adsorption, influx from the microcosm headspace, and Michaelis-Menten biodegradation. Fitting microcosm concentration versus time data to the model yields estimates of  $V$  and  $K$ , which in turn can be used in BV models. This microcosm model is also used in Richards, Ostendorf, and Switzenbaum (1992).

(5) Moyer (1993) presents an analytical model for column studies of BV, in which kinetic parameters are determined by modeling vertical profiles of hydrocarbon vapor concentration. These are compared with biodegradation kinetics for the same location at the same site determined from probe cluster data (Ostendorf and Kampbell 1991) and laboratory microcosms (Richards, Ostendorf, and Switzenbaum 1992). Agreement is good even though different models were used, and different concentrations and time and length scales were involved.

## 2-6. Use of Models in SVE/BV Strategy

Computer modeling is an important tool that can contribute significantly to all phases of an SVE/BV project. Readily available models are summarized in Appendix C. Use of models throughout an SVE/BV project is described below.

*a. Technology screening.* The technical feasibility of SVE/BV is typically related to required expenditures. The following question is often asked, "What would be the order-of-magnitude installation costs of an SVE/BV system?" Installation costs are controlled by the number of extraction points, the

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physical spacing of extraction points, the sizing/numbers of blowers required to extract vapors, and the type/size of offgas treatment equipment. Models can be used to quickly provide order-of-magnitude estimates of the total required airflow and the spacing of extraction points so that preliminary estimates of installation costs can be obtained. This preliminary modeling should not be substituted for pilot testing and detailed design. Typically, the effort includes modeling of a broad range of permeabilities, porosities, gas constants, gas molar masses, and viscosities to obtain maximum and minimum estimates of vapor production rates and numbers of extraction points. Contact between the modelers and the site characterization team is strongly encouraged. Screening models typically require no more than one or two days of labor by the project engineer. Significantly more effort is usually not appropriate if investigations have been limited and pilot testing has not been performed.

(1) Screening vapor transport models such as HyperVentilate and VENTING are typically used during the technology screening portion of a project to provide order-of-magnitude estimates of the time which would be required to remediate if SVE/BV was used. The programs can be used by most project engineers and simulations provide easy to understand output (e.g., mass of benzene extracted versus time). However, these models usually include at least one lumped parameter (e.g., removal efficiency) which accounts for the net effect of several factors. These lumped parameters have little physical meaning and the assumed value can significantly change the predicted vapor concentrations and remediation times. Therefore, novice modelers should always ensure that their work receives peer review from more experienced practitioners.

(2) A question which is often asked is, "What would be the O&M costs associated with the system and how long would the system be expected to operate (order-of-magnitude estimate)?" Simulations are performed assuming a range of plausible input parameters to estimate the concentrations of contaminants in offgas (so that treatment costs can be estimated) and to estimate the range of time which might be required to achieve remedial objectives (so that total O&M costs can be estimated). For example, screening simulations may be used to estimate that a hypothetical SVE/BV system for a moderately volatile compound would have an O&M cost of between \$20,000 and \$40,000 per year and may be expected to operate between 2 and 4 years. Therefore, O&M expenditures (not including installation costs or inflation) might range from \$40,000 to \$160,000. A parallel analysis might reveal that excavation with onsite bioremediation would cost \$70,000 to \$90,000 over a one-year period. In this scenario, it might be concluded that the short-term time frame and smaller potential cost range associated with the second remedial option would be preferred.

(3) Detailed vapor transport models are most often used to aid in the optimization of large SVE/BV systems with complicated contaminant distributions. Detailed vapor transport models are not usually used for small SVE/BV systems (e.g., less than five extraction points). In those scenarios, project engineers typically rely on empirical trends from pilot tests or from operation of the full-scale system to estimate times for completion of remediation.

(4) The construction of detailed vapor transport models almost always requires the input of several parameters that have not been measured (e.g., dispersion coefficients or partitioning coefficients). In addition, the calibration process often requires adjustment of parameters to achieve a fit between actual and simulated data. That process is very time consuming and requires considerable judgment based on experience. Consequently, experienced modelers should be used if detailed vapor transport modeling will be performed.

*b. Pilot test design.* When the decision has been made to pilot test an SVE/BV system, simple simulations are sometimes performed to aid in design of the pilot test. These simulations are typically

performed to estimate the range of vapor flow rates which might be expected from one extraction point so that the appropriate equipment is mobilized, and to estimate the potential discharge concentrations to select appropriate emissions treatment for the pilot test. In addition, simulations are frequently used to estimate the maximum and minimum potential radii of influence of the pilot extraction point so that observation points for measuring soil vapor pressures are located appropriately. These simple simulation efforts are typically performed in about one day.

*c. Extrapolation of pilot test data for full-scale design.* After pilot testing has been completed, the preliminary model is typically updated by calibrating the model to pilot test data.

(1) Perhaps the most useful application of pilot test data for design of full-scale systems is for determination of pressure and vacuum requirements. When the design flow rate has been selected, the pressure or vacuum required to achieve the design flow rate must be determined. Although vacuum at the well screen can be calculated using Equations 2-20 or 2-27, wellbore vacuums generally exceed these values due to well inefficiency. Unfortunately, well inefficiencies are difficult to predict, as they appear to be controlled by capillary pressure-saturation relations. Results of pilot test data, however, provide a direct measurement of the pressure or vacuum necessary to develop a particular flow rate. A plot of flow vs. vacuum obtained from stepped rate pumping tests can be used to determine pressure or vacuum requirements at the design flow rate. In conjunction with data regarding friction losses through piping and equipment, these data are used for equipment sizing and determination of system power requirements.

(2) The process includes incorporation of measured vapor parameters and permeability estimates followed by specification of the pilot extraction point location and vapor extraction rate which was used during the pilot test. The model is then run and simulated vapor pressure distributions are compared to actual measured vapor pressure distributions. The simulated pressure distributions will be different from actual distributions after the first run. This is usually due to soil permeability variations and unexpected boundary conditions (e.g., utility conduits). Because of this, calibration becomes an iterative process of slightly changing assumed soil properties and/or boundary conditions in certain areas followed by repeated runs until simulated pressure distributions are within an acceptable range of the measured distributions. The acceptable range is usually defined by the amount of error associated with the pilot test measurements.

(3) Once a model has been calibrated to pilot test data, the model can be used to simulate varied numbers, locations, and flow rates from/to extraction points and air injection points (see Figure 5-11). When a simulated scenario fulfills design criteria (e.g., sufficient contaminant removal within an acceptable time frame), the flow rates from extraction points are tabulated for specification of equipment and appropriate monitoring locations are chosen. The simulation process also includes a sensitivity analysis in which parameters (e.g., vapor temperature) are varied within a plausible range to determine the potential effect on predicted flow rates and pressure distributions. These sensitivity runs are used to ensure that specified equipment will be capable of handling the full range of potential pressures and flows.

*d. System operation.* Many large SVE/BV systems are anticipated to operate for several years. Modeling can help optimize operation of longer duration systems.

(1) All contaminated areas in these large systems will not be remediated at the same rate due to variations in soil conditions and contaminant concentrations. Consequently, certain portions of the system may be turned off earlier than other portions. Conversely, operational data may indicate the need to add vapor extraction or injection points in other areas. Models are sometimes calibrated to the operational data

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to allow the effects of turning off components to be predicted (often to fulfill a regulatory obligation) or to optimize the locations of potential system expansions.

(2) When portions of SVE/BV systems are turned off earlier than other portions, there is frequently a concern that contaminants may migrate back into areas which have been turned off, that contaminants may partition into the vapor phase from the sorbed phase, or that contaminants may slowly partition into the vapor phase from underlying groundwater which has not been fully remediated. Simulations may be performed to estimate if contaminant concentrations might "rebound" in areas where systems are turned off and to determine which operational changes would be required to prevent concentration "rebound." Appendix F presents a methodology for performing rebound assessments and the mathematical framework for interpreting rebound data.

## Chapter 3 Site Characterization and Technology Screening

### 3-1. Introduction

This chapter describes SVE/BV technologies and their applicability to different types of contaminants and sites. Guidance on screening level evaluation of SVE/BV is provided, along with several examples of screening evaluations.

### 3-2. SVE/BV Technology Options

To familiarize the reader with the range of technology variations available, the following subsections introduce various SVE/BV remedial options.

*a. Soil vapor extraction.* SVE can be a cost-effective way to remove VOCs from unsaturated soils. Other names for SVE include "soil venting," "soil vacuum extraction," "vacuum extraction," "subsurface venting," "soil gas vapor extraction," "in situ venting," "enhanced volatilization," and "vapor extraction."

(1) Airflow is induced in the subsurface by applying a pressure gradient through vertical or horizontal wells or horizontal trenches. In SVE, this is usually accomplished by withdrawal, rather than injection, of air. The SVE gas flow increases rates of contaminant mass transfer to air in the unsaturated zone by evaporation of NAPL, volatilization of contaminants dissolved in pore water, and desorption of contaminants from soil particle surfaces. SVE is dependent on contaminant properties, such as volatility, and soil properties, such as air permeability and stratigraphy.

(2) SVE is often used in conjunction with other remediation technologies that treat the resulting contaminated air and water streams. Sometimes ancillary technologies such as soil heating and subsurface fracturing are also used in an effort to further enhance transport rates. SVE is usually required in conjunction with air sparging systems to extract the generated contaminated air from the subsurface.

(3) SVE systems vary, but a typical SVE system schematic is provided in Figure 3-1. It consists of one or more extraction wells, an air/water separator, and a blower or vacuum pump. It may also include one or more air inlet or injection wells, an impermeable cap at the ground surface, and treatment systems for the air and/or water streams. Air may need to be filtered prior to injection. Contaminated condensate (water condensed from the extracted air stream) may be treated offsite.

(4) SVE treatment rates are highly site-specific, varying greatly as a function of such factors as air permeability, contaminant concentrations, cleanup standards, and offgas treatment system characteristics. The number of pore volume exchanges necessary to complete a cleanup is likewise highly variable, but a typical number might be 5,000 pore volumes (Beckett and Huntley 1994). To complete remediation in 1 to 2 years would necessitate about 10 pore volume exchanges per day.

(5) In the United States, SVE has been used at leaking UST sites and for methane removal at landfills since the 1970s (Emcon 1980; U.S. District Court 1994). Thornton and Wootan (1982) discussed the

concept of vertical vapor extraction to remove gasoline. Texas Research Institute (1984) presented various venting geometries and described a venting test in a pilot-sized soil tank. Marley and Hoag (1984) conducted laboratory SVE tests on packed gasoline-contaminated soil columns and measured and modeled the concentrations of gasoline constituents in the extracted gas. Hoag and Cliff (1985) reported on SVE of gasoline-contaminated soil at a service station; 1,330 liters of gasoline were removed in 100 days, achieving cleanup levels of 3 ppm or less in soil vapor and nondetectable concentrations in soil. Other early field applications for hydrocarbon removal are described in Batchelder, Panzeri, and Phillips (1986), Crow, Anderson, and Minugh (1986), and USEPA (1989a). Some of the early applications of SVE to solvents and other hazardous wastes are summarized in USEPA (1989a). USEPA documents six Superfund Remedial Actions at which SVE has been completed, including a 53,500 m<sup>3</sup> portion of the Rocky Mountain Arsenal contaminated with tetrachloroethylene (PCE) and 1,480,000 m<sup>3</sup> at Fairchild Semiconductor contaminated with chlorinated hydrocarbons (USEPA 1993b). SVE is widely used in Europe (Hiller 1991, Dieter Baumgarten, personal communication, 1999).

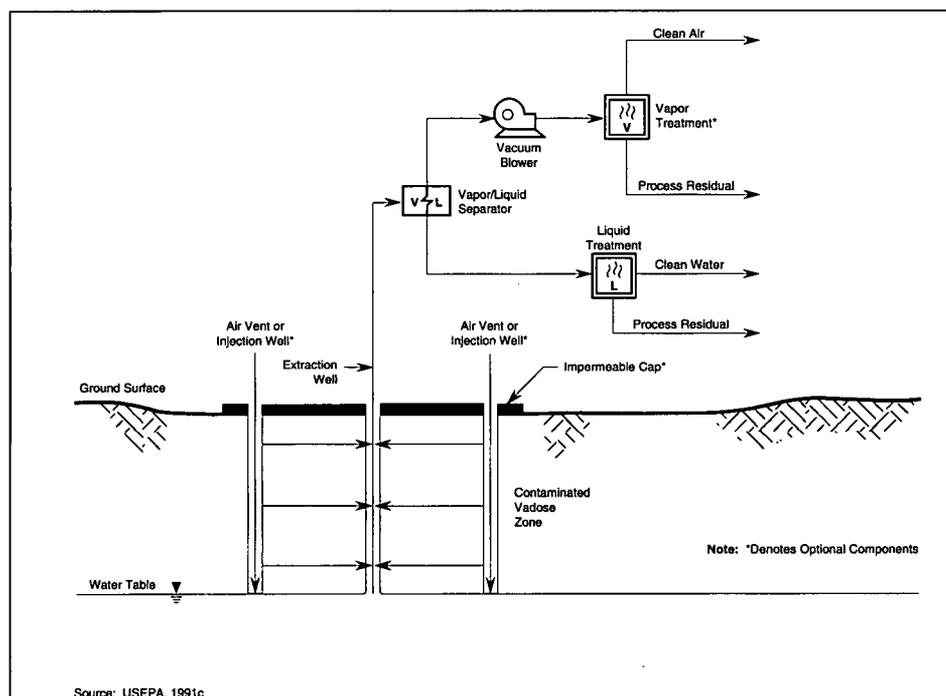


Figure 3-1. Generic soil vapor extraction system.

*b. Bioventing.* BV is the process of advecting gases through subsurface soils to stimulate in situ biological activity and enhance bioremediation of contaminants. It generally involves supplying oxygen in situ to oxygen-deprived soil microbes by forcing air through unsaturated contaminated soil at low flow rates (Hoepfel, Hinchee, and Arthur 1990). Compounds that are readily aerobically biodegradable in the vadose zone include linear (and some branched) alkanes; mono-aromatic compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX); and, to a somewhat lesser extent, two-ring aromatic compounds such as naphthalene.

(1) Co-substrates such as methane and nutrients such as ammonia can also be introduced into the subsurface in the gaseous phase. Airflow can be induced by air injection or withdrawal. Air injection is often preferred because it may eliminate the need for offgas treatment (Figure 3-2); however, air

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withdrawal and treatment may be preferred if there is a concern that vapors could migrate to nearby basements or other structures.

(2) BV is similar to SVE, but its primary goal is different. They both usually involve volatilization and biodegradation, but whereas the goal of SVE is to volatilize and remove the air phase contaminants from the subsurface as quickly as possible, BV attempts to maximize the rate of biodegradation. BV utilizes low airflow rates to provide only enough oxygen to sustain optimal microbial activity (e.g., vapor-phase oxygen concentrations at or above 5 percent). Hinchee, Arthur, and Miller (1991a) state that approximately one pore volume exchange of air per day is sufficient to support biodegradation, while more recent field

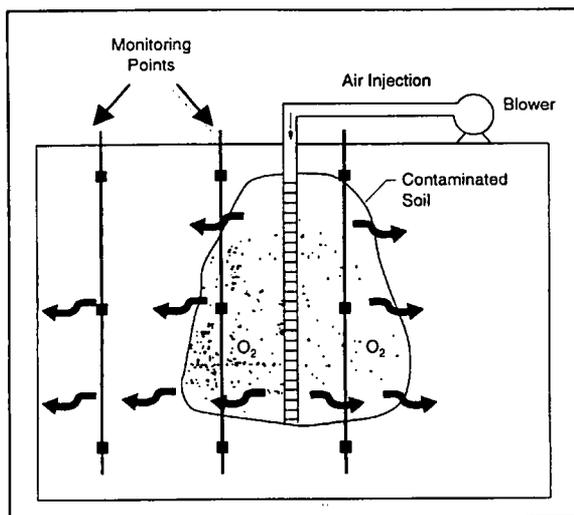


Figure 3-2. Typical bioventing system (AFCEE, 1994).

experience with full-scale BV systems suggests that 0.25 to 0.5 pore volumes may be optimal in terms of maximizing biodegradation while minimizing volatilization. This lower exchange rate minimizes the mass of volatilized contaminants in offgas that may need to be treated aboveground, and increases the residence time of volatilized contaminants in the subsurface for maximum destruction by biodegradation. Whereas SVE is limited to treating volatile contaminants, BV can also be used to remediate contaminants of low volatility such as fuel oil and diesel constituents (Miller et al. 1993). The remediation time frame for such low-volatility and low solubility contaminants may be long, however.

(3) Studies in the early 1980s by Texas Research Institute (1980, 1984) first indicated that SVE stimulated biodegradation, which may have accounted for as much as 38 percent of the removal of gasoline from the vented soils. During the same period, researchers conducting experiments for Shell Research in the Netherlands made the first field observations of venting-induced biodegradation (van Eyk and Vreeken, 1988). Wilson and Ward (1986) proposed using air to enhance biodegradation in the unsaturated zone, and Bennedsen, Scott, and Hartley (1987) concluded that SVE is an effective way to provide oxygen to the subsurface for enhanced biodegradation. Natural biodegradation occurs in the subsurface, but at rates dependent on oxygen diffusion (Ostendorf and Kampbell 1989, 1991). In the late 1980s and early 1990s, the U.S. Air Force (USAF) carried out field-scale SVE and bioventing research at several bases, including Hill AFB in Utah and Tyndall AFB in Florida (DePaoli et al., 1991; Miller et al., 1991). This work was expanded to include bioventing testing at over 125 sites, in an effort the Air Force Center for Environmental Excellence (AFCEE) termed their Bioventing Initiative (Miller et al., 1993; AFCEE, 1996). The USAF now considers bioventing to be a presumptive remedy for sites contaminated with jet fuel. Recommendations stemming from the Bioventing Initiative are provided in Principles and Practices of Bioventing (Leeson and Hinchee, 1995).

*c. Passive Venting.* Although in most cases mechanical blowers are used to induce the air movement for either SVE or bioventing, natural barometric pressure changes can be used to induce air flow to or from the subsurface. The key site condition is the presence of some near-surface (or at least above the zone to be treated) stratum or barrier that causes a delay of the response of the subsurface pressures to the changes in atmospheric pressure. This pressure "lag" results in a differential pressure that can be a driving gradient to induce air flow through the "short-circuit" presented by the SVE or BV well. Atmospheric pressure

changes on the order of 25 cm of water during the passage of storms can generate significant flows, especially if the changes occur rapidly, the target zone has reasonably high air permeability, and the isolating stratum is quite tight. The daily heating of the atmosphere can also cause a pressure differential that can drive air into the subsurface during the night or extract air during the day. In order to prevent the alternating air entry and withdrawal, check valves are installed on the tops of the SVE or BV wells to limit the flow to one direction and improve effectiveness (Rossabi et al 1999). Since there is little available driving pressure, the use of passive extraction would not generally be consistent with the need for offgas treatment devices that require a pressure to deliver the offgas. The use of passive venting should be considered for remote sites or for sites that have had most of the required remediation through more aggressive treatment and a polishing phase is required before site closeout.

*d. Combined soil vapor extraction/bioventing.* As described in the previous section, the processes of volatilization and biodegradation are often hard to separate and thus SVE and BV can often be used together in a beneficial way. Whether to apply SVE, BV, or both at a site will depend on a number of factors, but the following general guidelines are suggested.

(1) At one extreme, SVE alone should be applied at sites where only volatile compounds which are difficult to biodegrade are present. BV alone should be applied at sites where only biodegradable compounds of low volatility are present or where low-to-moderate concentrations of volatile biodegradable compounds are present. A combined SVE/BV approach could be used at sites with:

- High concentrations of volatile biodegradable compounds (remove large amounts of contaminant mass and prevent air emissions with SVE, followed by polishing using BV).
- Volatile biodegradable compounds in sensitive areas where rapid response is critical.
- Both biodegradable and non-biodegradable volatile compounds.

(2) In a combined remediation system, SVE is implemented as an initial phase followed by BV as a second phase. In situ remediation of JP-4 jet fuel contamination at Hill Air Force Base in Utah used a combined approach (DePaoli et al. 1991c; Dupont, Doucette, and Hinchee 1991), as was remediation of an automobile repair facility where leaking underground storage tanks had released gasoline, waste lubrication oil, and hydraulic oil to the unsaturated zone (Zachary and Everett 1993). A combined approach would often attempt to remove the volatile contaminants first by SVE and then biodegrade the less volatile contaminants with BV. The process would change from vacuum extraction (SVE) to an air injection mode (BV) in many cases. Airflow rates would also change, possibly necessitating a smaller blower for the BV phase of operation to maximize efficiency. Paragraph 5-2a, provides further guidance pertaining to the design of combined SVE/BV systems. Note that based on USACE experience the time necessary for bioremediation of the low-volatility compounds may be long and that low clean-up goals may be difficult to achieve. However, the residual petroleum contamination generally has low mobility and low toxicity.

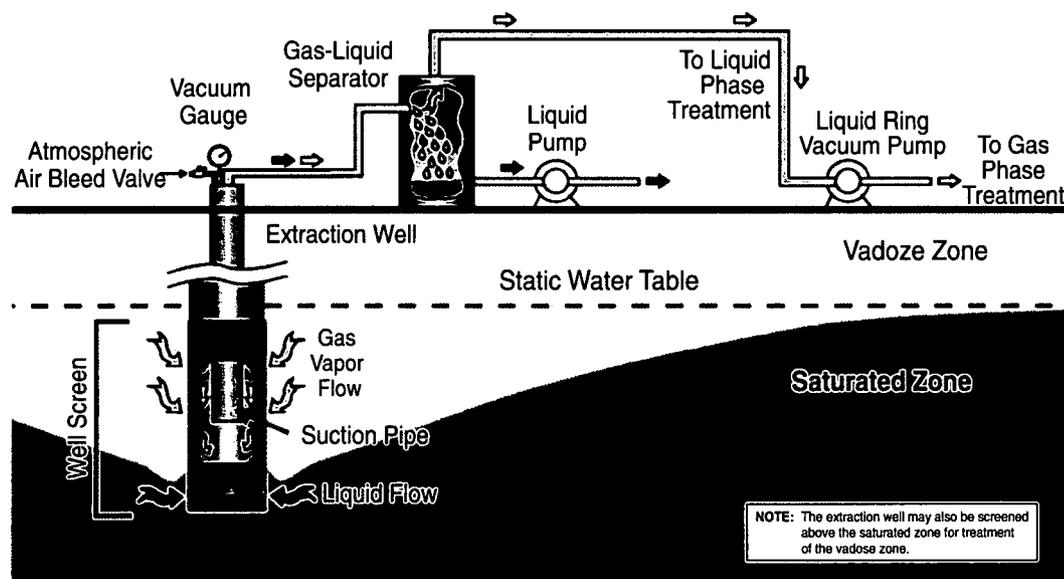
*e. Multi-Phase Extraction.* Multi-Phase Extraction (MPE) entails simultaneous extraction of vapor phase, dissolved phase and separate phase contaminants from the vadose zone, capillary fringe, and saturated zone. It is a modification of SVE that allows this technology to be extended to moderately permeable soils (intrinsic permeability  $10^{-8}$  to  $10^{-10}$  cm<sup>2</sup>). Refer to Engineer Manual 1110-1-4010, Multi-Phase Extraction for a detailed discussion of this technology. In general, MPE works by applying a high vacuum (relative to SVE systems) to a well or trench that intersects the vadose zone, capillary fringe and

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saturated zone. Because the resulting subsurface pressure is less than atmospheric, groundwater rises (upwells) and, if drawn into the well, is extracted and treated aboveground before discharge or re-injection.

(1) There are a variety of implementations of MPE. The terminology presented by EPA (1997), distinguishes the variations of this technology as: "two-phase extraction" if liquids and gases are extracted within the same conduit; and "dual-phase extraction" if separate conduits for vapor and liquids are used. TPE is also sometimes referred to as "bioslurping", primarily when used for vacuum-enhanced LNAPL recovery.

(a) Two-phase extraction (TPE). During TPE, soil gas and liquid are conveyed from the extraction well to the surface within the same conduit, which has been referred to with various names including "drop tube", "slurp tube", "stinger", "lance", or "suction pipe". A single vacuum source (vacuum pump or blower) is used to extract both liquid and gaseous phases. A common configuration is depicted in Figure 3-3. The suction pipe suspended within the well casing extracts a combination of liquids (NAPL and/or groundwater) and soil gas. These phases are conveyed to an aboveground gas-liquid separator. If extraction of NAPL is anticipated, an oil-water separator may be installed downstream of the gas-liquid separator.



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Figure 3-3. Schematic of a TPE System, showing all fluids extracted from the well via the same suction pipe. (After EPA 1997)

(b) Dual-Phase Extraction. During DPE, soil gas and liquids are conveyed from the extraction well to the surface in separate conduits by separate pumps or blowers. A common "pipe within a pipe" configuration is depicted in Figure 3-4. It shows that a submersible pump suspended within the well casing extracts liquid, which may be NAPL and/or groundwater, and delivers it through a water extraction pipe to an aboveground treatment and disposal system. Soil gas is simultaneously extracted by applying a vacuum at the well head. The extracted gas is, in turn, conveyed to a gas-liquid separator prior to gas phase treatment. DPE is in essence a rather straightforward enhancement of SVE, with groundwater recovery being carried out within the SVE well. Other DPE configurations are also common, such as use of suction

(e.g., exerted by a double-diaphragm pump at the ground surface) to remove liquids from the well, rather than a submersible pump (Blake and Gates 1986). A line-shaft turbine pump could also be employed to remove liquids from the well, provided the water table is shallow enough.

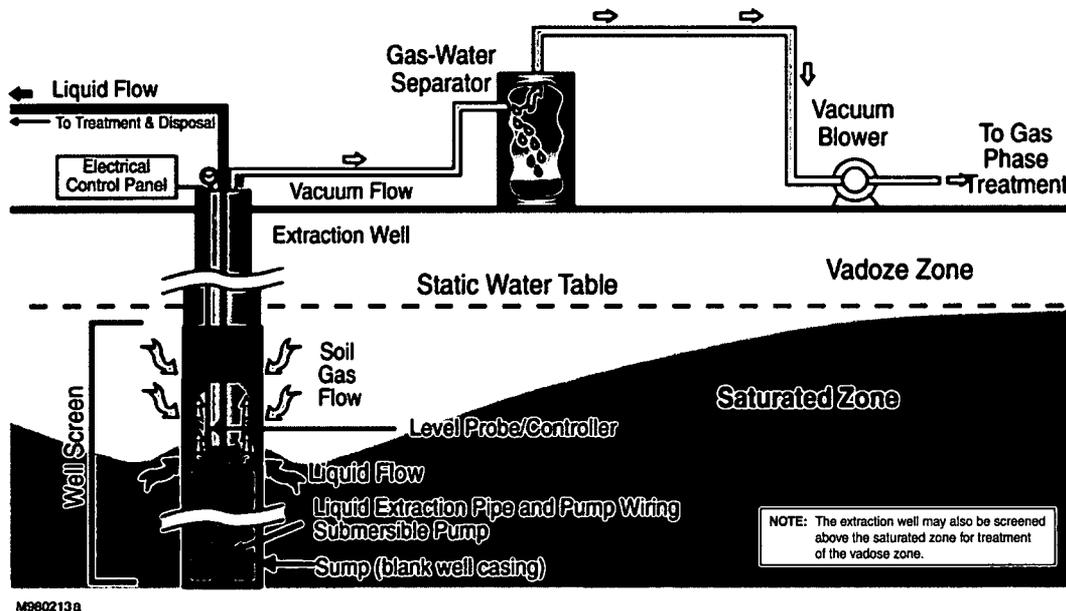


Figure 3-4. Dual phase extraction recovery system schematic showing separate liquids and vapor extraction conduits within the same well (After EPA 1997).

(c) Bioslurping, is a form of TPE that aims to enhance the recovery of LNAPL, while also stimulating BV within the unsaturated zone (AFCEE 1994a; Kittel et al. 1994; AFCEE 1997). A bioslurper uses a suction tube positioned near the LNAPL-water interface to induce a pressure gradient causing water, LNAPL and gas to flow into the well. A common bioslurping configuration is depicted in Figure 3-5. As with TPE, water and/or LNAPL that is drawn into the well is lifted and conveyed to a gas-liquid separator. The liquid phase is subsequently conveyed to an oil-water separator. Bioslurping systems are designed and operated in a manner that maximizes LNAPL recovery while minimizing groundwater and gas-phase recovery. The BV aspect of bioslurping is generally less important than the primary objective of enhancing free-product recovery.

(d) The three main strategies for applying MPE are: i) vacuum-enhanced recovery of NAPL, ii) vacuum dewatering to enable SVE and/or BV to remove and/or treat organic contaminants via the gas phase, and iii) vacuum-enhanced recovery of groundwater. This last strategy is not a variation of SVE, and so is not described here.

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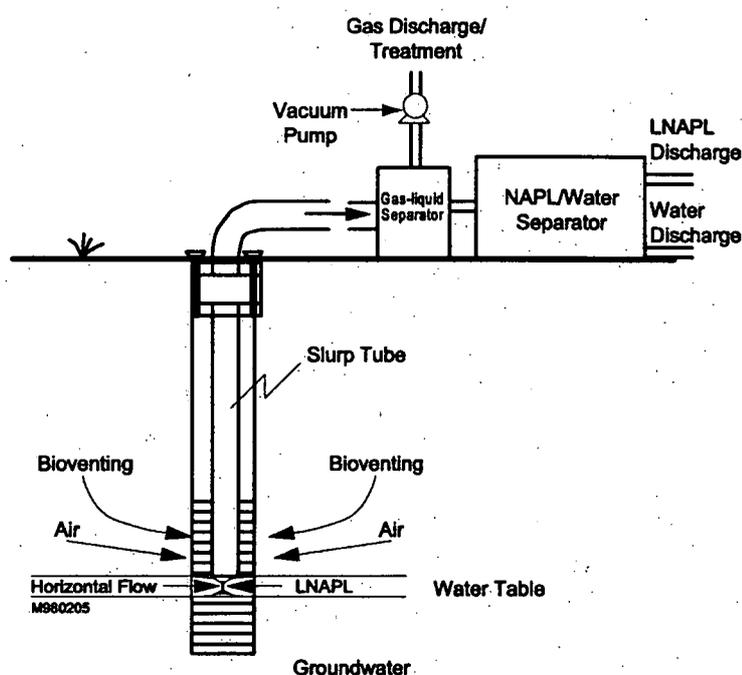
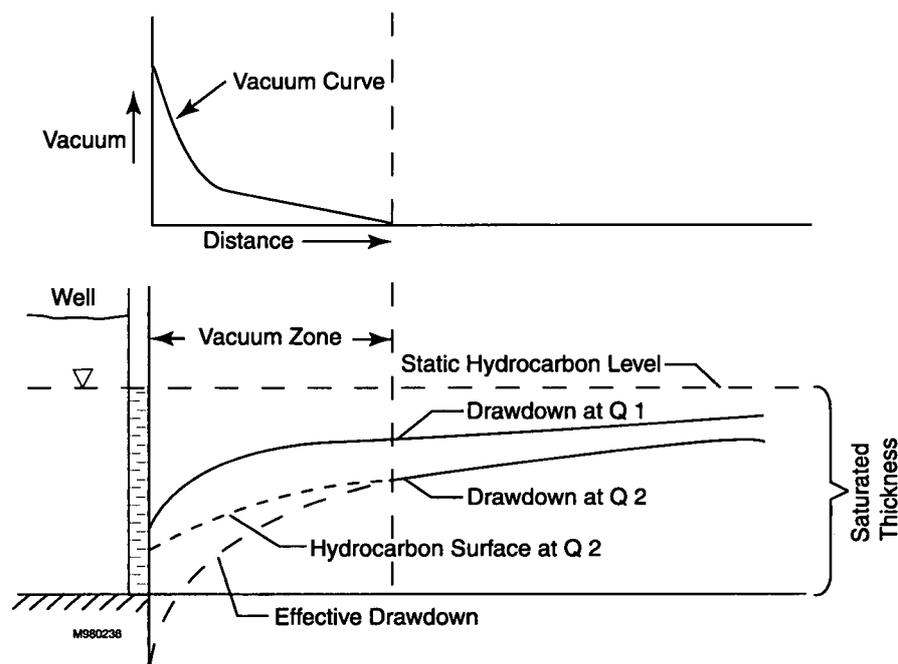


Figure 3-5. Bioslurper system (after AFCEE 1994). Not shown in this figure is the water table upwelling that occurs around the well when a vacuum is applied.

(e) Vacuum-Enhanced LNAPL Recovery. Vacuum-enhanced free-product recovery (Blake and Gates 1986; Hayes et al. 1989; API 1996) is employed, usually in medium-textured soils, to increase recovery rates of LNAPL relative to those that can be obtained using conventional means. The application of a vacuum to a recovery well increases the extraction flow rate without inducing a physical cone of depression (Blake and Gates 1986). In cases where physical drawdown is used in combination with vacuum enhancement, the effective drawdown, by superposition, is the sum of the induced vacuum (expressed in water equivalent height) and the physical drawdown, as shown in Figure 3-6. The gradient of hydraulic head that is the driving force for flow of liquid to the well is thus increased. Consequently, the volume of water extracted typically increases to an even greater extent than does the volume of LNAPL. Vacuum-enhanced recovery may also mobilize some of the LNAPL that would not otherwise be able to drain into a well because it is retained by capillary forces (Baker and Bierschenk 1995). Offsetting the increase in LNAPL removal is the necessity to treat and/or discharge a larger volume of extracted groundwater and an extracted gas stream.



**Figure 3-6. Schematic of Vacuum Effect on Perched Hydrocarbons. Q1 is extraction rate without application of vacuum; Q2 is extraction rate with application of vacuum. (Blake and Gates 1986. Reprinted by permission of National Ground Water Association. Copyright 1986. All Rights reserved.) Not shown in this figure is the water table upwelling that occurs around the well when a vacuum is applied.**

*f. Dewatering to Enable SVE/BV.* In low to moderately permeable formations that are in relatively close proximity to the capillary fringe, SVE and BV tend to have limited effectiveness. While air can flow through air-filled passages, it cannot flow through pores in such formations that tend to be saturated with water. The process of applying a vacuum to the soil to accomplish SVE also causes the water table to rise locally, or upwell, further limiting the zone through which air can flow. By removing both water and gas from the subsurface, these limitations, to some extent, can be overcome. Vacuum dewatering (Powers 1992) has had decades of use in the construction industry, where it is generally used to remove water from medium- to fine-textured soils that would otherwise flow into excavations made below the water table. When performed in VOC-contaminated soil, vacuum dewatering permits the flow of air through some of the previously saturated soil, thereby allowing VOCs residing there to partition into the air stream. In addition, soluble VOCs present in the extracted groundwater are also removed (USEPA 1997a). When carried out in soils contaminated with semi-volatile organic compounds (SVOCs) that biodegrade under aerobic conditions, vacuum dewatering enhances the aeration of previously saturated soil, thus stimulating in-situ aerobic biodegradation. It can also result in an increase in the dissolved oxygen (DO) content of soil pore water, helping to further enhance aerobic biodegradation in soil that is not able to be desaturated. It is important to underscore that compared to most other regions above the water table, the zone where air permeability is quite low (the capillary fringe) will transmit very little airflow during SVE or BV operation. Since in the case of LNAPL releases, this zone also tends to contain much residual LNAPL contamination (i.e., within the unsaturated portion of the smear zone), the problem of addressing the residual LNAPL is compounded unless the smear zone can be dewatered and exposed to airflow (Mickelson 1998). MPE offers a means to overcome this problem (Peargin et al. 1997).

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g. *In situ heating.* Heat may be applied to subsurface media with the goal of increasing the rate of contaminant volatilization and subsequent removal by SVE/BV. Increased subsurface temperatures serve to increase contaminant vapor pressure and solubility while promoting biotransformation and desorption. Increased temperatures also decrease the viscosity and interfacial tension of NAPL (EPA 1997b).

(1) Techniques that have been field tested for increasing subsurface temperatures include: steam or hot air injection, radio-frequency heating (RF), electrical resistance heating, and thermal conduction heating (In situ Thermal Desorption). Other potential in situ heating techniques can also be considered based upon site-specific availability of heating sources.

(2) Steam Injection. Steam injected into a series of boreholes above and/or below the water table elevates temperatures and creates thermal gradients that expedite volatilization and subsequent vapor removal by SVE and increases both dissolved contaminant and separate-phase liquids recovery (USEPA 1998, USEPA 1997b, Udell 1996)

(a) Several demonstrations of the benefit of steam injection have been documented. Injection of steam for the remediation of the unsaturated zone at Livermore National Laboratory (Newmark and Aines 1995) has been successful.

(b) The use of steam injected at depth has been shown to create upward thermal convection which can facilitate the removal of contaminants by SVE (Adams, Smith, and Basile 1992). The most notable success of steam injection for remediation has been the Southern California Edison wood treating site in Visalia, California. The injection of steam increased mass recovery of creosote and related compounds approximately a thousand-fold relative to pump-and-treat. The injection of steam at the Visalia site dramatically increased the recovery of NAPL, mostly as a NAPL-in-water emulsion. Mass removal through volatilization and NAPL recovery accounts for much of the mass removed, but the destruction of some of the contaminants in-situ via hydrous pyrolysis oxidation (HPO) has been considered an important mechanism as well (Leif, et al. 1998)

(c) Recent work by Udell and Richardson (personal communication, 1999) has indicated that biodegradation of many hydrocarbons by thermophilic bacteria can be an important process during steam injection and particularly, as the soils cool, if air is injected as an oxygen source. Pulsing of steam into the subsurface followed by active depressurization ("huff and puff") can promote the removal of contaminants from low permeability layers, if they are not too thick, through spontaneous boiling of pore fluids following the cessation of injection and with a sudden decline of pressure in adjacent high permeability layers through application of higher vacuums. Hot air injection, alone or in conjunction with steam injection, has also been demonstrated to accelerate soil/groundwater clean-up (Stewart et al., 1998). By using hot air instead of steam, less water is injected into the subsurface and thus less contaminant dissolution and migration occurs and less water must be pumped and treated to contain it. Note that the heat content of air is much lower than the total heat content of steam (primarily due to the heat released during the phase transition from steam to water), therefore, the thermal effects of the injection of the same volume of steam will be much more significant than for the same volume of hot air.

(3) Radio-Frequency heating. RF electrical energy can also be used to heat contaminated soil. The resulting elevated temperatures can result in volatilization of the contaminants present in the soil through a combination of evaporation, steam distillation, and steam-assisted evaporation. The volatilized contaminants are then removed by an SVE system. An electrode array is installed in a series of drilled

boreholes and connected to a surface power supply. Technology descriptions claim that soil temperatures greater than 300 °C can be achieved using this method. Although temperatures significantly above 100 °C have been observed during RF heating, at the field scale temperatures above 100 °C tend to be confined to close proximity to the antenna, particularly in wet soils. It appears that the RF energy is converted to heat right at the antennae, due to what is termed a "skin effect", and that the major transport mechanism for heat away from the antennae is thermal conduction, not radiation. Thus the antennae function as complex (expensive) thermal conduction heaters. The cost of the process is a function of soil volume, soil moisture content, and final treatment temperature, among other factors. The cost estimates reported by EPA in the CLU-IN database range from \$100 to \$250 per cubic yard, depending on the volume of soil that must be treated. When this technology is used to raise the soil temperature to around the boiling point of water, the same phenomena of in situ pyrolysis, thermal oxidation, and enhanced biodegradation may occur as in steam injection.

(4) Electrical resistance heating. This mechanism of soil heating relies on resistive dissipation of electrical current passed through the subsurface. As soil and groundwater are heated to water's boiling point, the water turns to steam, stripping volatile and some semi-volatile contaminants from the pore spaces. Six-phase soil heating (SPSH) is the most common application of this technique. SPSH uses voltage control transformers to convert conventional three-phase electricity into six electrical phases (Gauglitz et al. 1994a, b). These electrical phases are then delivered to the subsurface by vertical, angled or horizontal electrodes installed using standard drilling techniques. Electrodes are inserted into the ground in one or more circular arrays of six electrodes per array. Water in the soil pores conducts the electrical energy between each pair of out-of-phase electrodes. Resistance to current flow causes soil heating. A seventh neutral electrode located at the center of the array doubles as an SVE vent. Use of conventional utility transformers for SPSH results in capital costs that may be as little as one-fifth to one-tenth those for RF heating or microwave heating (Gauglitz et al. 1994b). An early SPSH field demonstration was conducted at the Savannah River Site, SC (SRS) at a location containing very low permeability clay soils contaminated with PCE and TCE. (This demonstration was part of the Volatile Organic Compounds in NonArid Soils Integrated Demonstration at SRS.) The soils were heated to 100°C and more than 99 percent of the contamination was removed, while a substantial volume of water was also removed from the soil in the form of steam (EPA 1997). SPSH also shows promise for enhancement of BV (Heath and Truex 1994). Since the soil's electrical conductivity decreases dramatically upon desiccation, this technology heats the soil to a maximum temperature of the boiling point of water. The same phenomena of in situ pyrolysis (HPO), thermal oxidation, and enhanced biodegradation can occur as described for steam injection.

(5) Electrical Conduction Heating or In Situ Thermal Desorption (ISTD). ISTD affects remediation by applying heat and vacuum to the subsurface to vaporize and destroy contaminants in situ, and/or extract the vapors and treat them above-ground. ISTD uses technology first developed in the petroleum industry for production of heavy oil, including the use of thermal wells for conductively heating the soil, and combined vacuum/heater wells for inducing flow of vapors to an aboveground treatment unit. ISTD operates at substantially higher temperatures than the other in situ heating technologies (except in situ vitrification, which melts the soil), achieving temperatures approaching 700°C. Due to the relatively long residence times during which vaporized contaminants are exposed to elevated temperatures near the heater-vacuum wells, contaminants are mostly converted to CO<sub>2</sub> and water (Vinegar et al 1998, Stegemeier and Vinegar 2000). Since ISTD operates at such high temperatures, it can be used for virtually any organic contaminant. Contaminants that have been treated by this method include PCBs, chlorinated solvents, fuel oil, coal tar compounds (PAHs), pesticides and dioxins. Removal efficiencies using ISTD are typically very high, and since this technology relies on conduction of heat through the soil, it can be applied effectively in heterogeneous and low permeability soils. The main drawback of this technology is that the heater wells

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must be installed at relatively small intervals, 5 to 10 feet, thus often requiring many wells and substantial capital investment. Recent advances in heater and heater-vacuum well design enabling installation using direct-push methods under a wide range of subsurface conditions hold promise of substantially reducing such costs.

(6) Alternative heating techniques can be considered in addition to those described. For example, waste heat from thermal oxidizer units can be used for in situ heating via injection wells. However, direct reinjection of thermally treated offgas into the subsurface may inhibit biodegradation if the injected gas is depleted of oxygen. The low heat capacity of air relative to water and soil limits the amount of heat that can be delivered to the subsurface and the subsurface temperature rise that can be achieved. Heat can also be introduced using buried heating cables or by infiltration of heated water (Sayles et al. 1992).

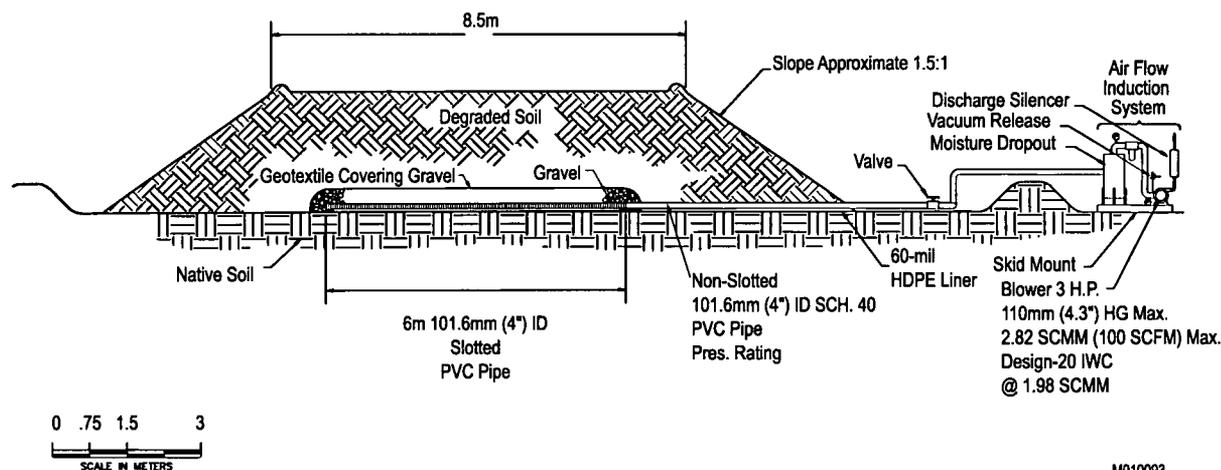


Figure 3-7. Aboveground soil pile (cross section)

*h. Aboveground piles.* In many instances site, operational, or regulatory constraints require that impacted soils be removed prior to treatment. Also, when USTs are removed, grossly contaminated soils will often be excavated and stockpiled before backfilling the excavation pit. In such circumstances, an alternative soil treatment method may employ an aboveground soil pile with a network of aeration pipes and mechanical blower(s).

(1) The design of an aboveground soil pile is relatively simple. A low permeability liner, typically constructed of high-density polyethylene or other synthetic material, is constructed to contain water drainage. A network of slotted pipes connected to a manifold system is placed on the liner. For an SVE application, the manifold is connected to the vacuum end of a blower to create a negative pressure in the perforated pipes. The negative air pressure at the base of the aboveground soil pile will cause air to be drawn through the soils. Extracted soil vapors can be trapped or destroyed using applicable emission control equipment. For a BV application, air can be extracted or injected, and biological activity is often further promoted in a soil pile treatment system by the addition of water, nutrients, and/or heat. Supplemental moisture can be supplied to the soil pile with a flood irrigation or sprinkler system, and a leachate collection system may need to be provided. In most cases a synthetic liner covers the entire soil pile. Air entry points are established when liners are used to ensure aeration of the pile while minimizing the entry of precipitation into the soil matrix. Piles left uncovered, or with a vegetative cover only, are at

risk of experiencing limited aeration due to saturation of the soils from rainfall infiltration. As in in situ remediation, aboveground piles may be operated in an SVE mode initially, followed by a BV phase in which air is injected. The considerations noted in paragraph 3-2c also apply here. Review of literature related to biopile construction design shows a wide variety of configurations. Space availability and logistics rather than size based performance standards often times dictate biopile dimensions. An important practical limitation on the size and geometry of the soil pile is whether the pile dimensions exceed the reach of a front-end loader. Construction complexity and the likelihood of compaction increase with larger biopiles. For this reason it is recommended that biopiles do not exceed a height of 8 feet (2.4 m). In addition, piles in excess of 10 feet in height generally require more than one level of aeration pipes. This adds further complications to the construction process. A single set of aeration pipes located at the bottom of the central portion of the biopile is sufficient for piles up to 8 feet high. Length and width dimensions are flexible and site specific but in general the shape of the pile should be long and narrow. This configuration will allow for easy construction by a front loader without compaction of the soil. An appropriate volume for a biopile is 500 cubic yards. This size is sufficiently large for the treatment of a significant volume of soil yet small enough to allow for easier aeration throughout the pile. In addition piles of this size are manageable enough so two workers are able to apply and remove the impermeable cover should nutrient addition or soil sampling be necessary. (Biopile Design and Construction Manual (TM-2189-ENV) Naval Facilities Engineering Service Center (NFESC 1996)). Figures 3-7 and 3-8 illustrate a typical soil pile design (see also Athey and Wrenn 1993).

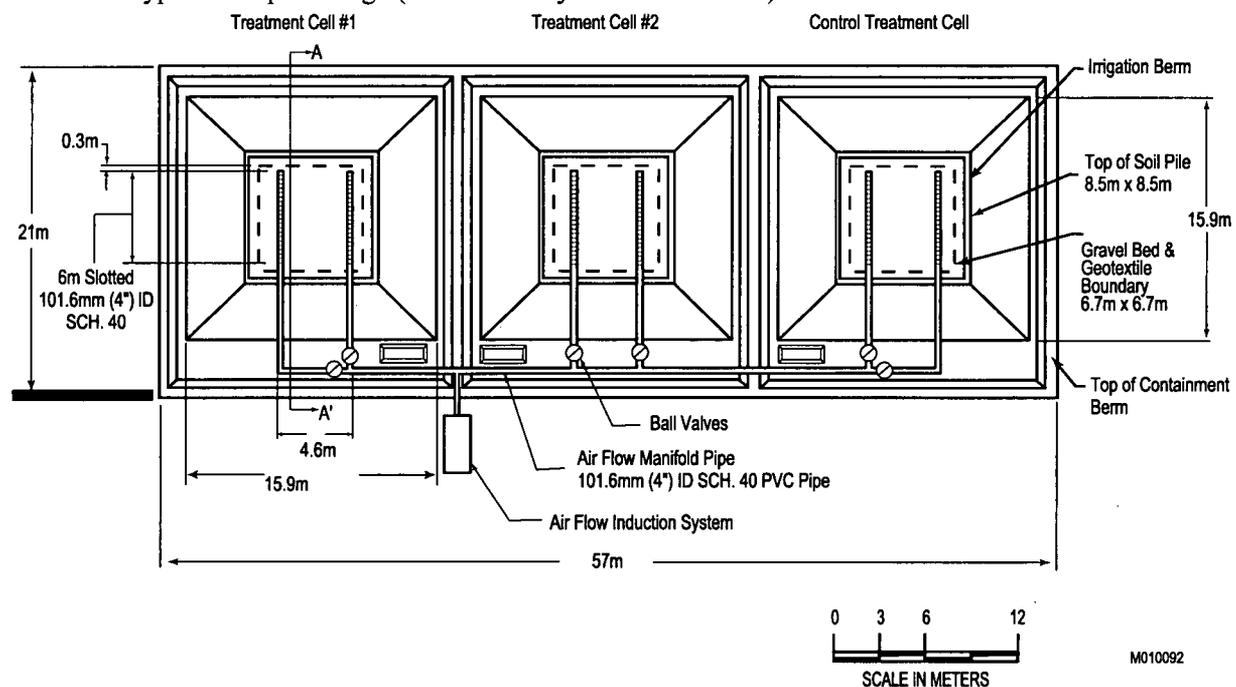


Figure 3-8. Aboveground soil piles (plan view)

An advantage of an aboveground soil pile is that space requirements for soil treatment can be minimized relative to some other ex-situ treatment methods. For example, in land-farm applications where aeration is achieved by tilling, the optimum treatment zone thickness is limited to approximately 0.3 meters. In contrast, an aboveground soil pile that employs aeration pipes and blowers can increase the treatment zone thickness to about 1.2 to 3 meters. Operational costs for an aboveground soil pile system are essentially fixed for a given level of contamination and are not strongly dependent upon the size of the soil pile. Only routine inspection of the blower unit and operation of an irrigation system (if biodegradation processes are optimized) are required, and time requirements for each activity vary little in relation to treatment system

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size. Other advantages include the potential for constructing a closed treatment system where all fluids can be captured and recycled. Also, excavated soils may be modified or augmented, for example, with bulking agents during transfer to the soil treatment system to mitigate factors that limit remediation. Treatment times may be shorter than those of in situ treatment processes. A primary disadvantage of this soil treatment approach is that significant labor and equipment costs are associated with excavation, soil handling, and possibly air emissions control during transfer of soil to the treatment system. Other disadvantages are that soils need to be moved again after treatment, and space requirements are greater than for in situ treatment methods.

*i. Ancillary technologies.* Other remediation technologies are often applied with SVE/BV. These include air sparging, injection of gases other than air, and pneumatic and hydraulic fracturing.

(1) Air sparging. Air sparging, also referred to as "in situ air stripping" or "in situ air sparging," is used in conjunction with SVE/BV as a means of removing contaminants from soils and groundwater in both the saturated and unsaturated zones. Upon injection below the water table, air rises toward the surface in air channels, stripping dissolved, adsorbed, and liquid VOCs. The vapor phase VOCs are transferred to the vadose zone, where they can be collected by SVE. By increasing the oxygen content in the saturated and unsaturated zones, air sparging can provide the additional benefit of enhancing aerobic biodegradation of constituents which may not have volatilized (Brown and Fraxedas 1991). Refer to Engineer Manual 1110-1-4005, In-Situ Air Sparging for a detailed discussion of this technology.

(a) Air sparging systems are often used in conjunction with SVE so that the volatile contaminants stripped from the saturated zone can be captured upon reaching the vadose zone. Due to the positive pressure gradient induced by the injection of air, the use of air sparging without SVE could potentially lead to the uncontrolled migration of contaminants into previously unaffected areas, including basements or utility conduits, creating potential explosion or health hazards.

(b) Under favorable soil and contaminant conditions, air sparging can be a timely and cost-effective method for remediating groundwater contamination (Marley 1992). A typical application of an air sparging process would take place in an unconfined, highly permeable aquifer with limited stratification exhibiting VOC contamination. Design considerations include depth to groundwater, contaminant solubility, biodegradability, vapor pressure, soil type, soil organic carbon content, degree of soil heterogeneity, presence of subsurface confining layers, and presence of NAPL.

(c) Air sparging systems commonly consist of the following components: sparge well(s), air compressor, air extraction well(s), a vacuum pump or blower, vapor pretreatment equipment, an offgas treatment system, and associated piping and instrumentation (Johnson et al. 1993). A typical air sparging configuration is presented in Figure 3-9 (USEPA 1992).

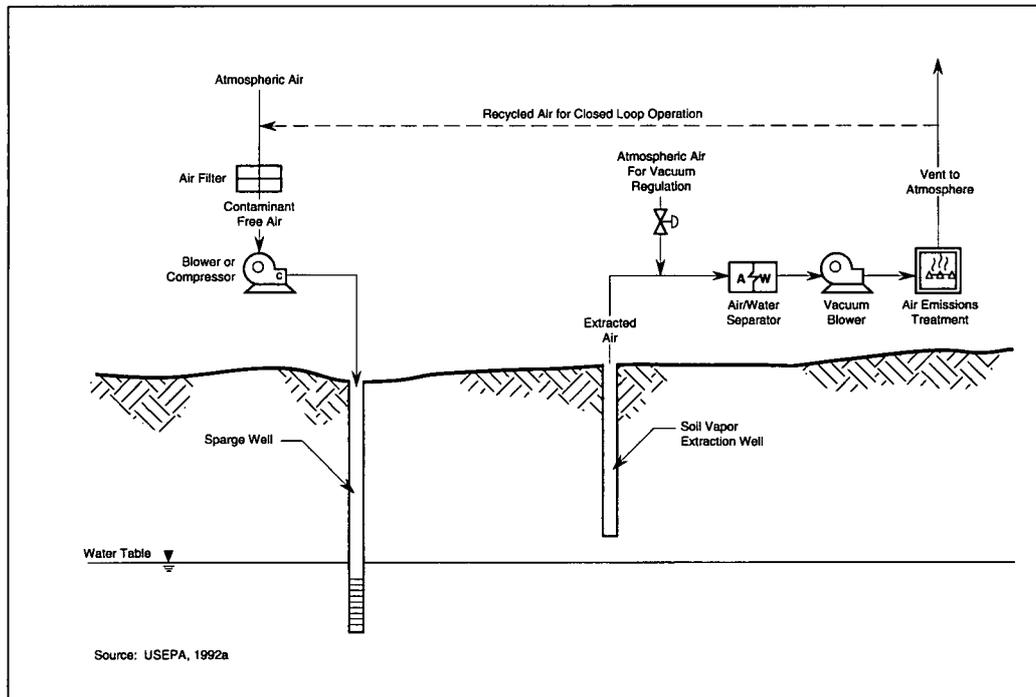


Figure 3-9. Air sparging process schematic.

(d) The effectiveness of air sparging depends largely on the distribution of air. In many cases, sparged air has not become well distributed within the treatment zone and flows through preferential pathways and thus bypasses significant portions of the treatment zone (Baker, Hayes and Frisbie 1995). The determination of the likely distribution of air during sparging is important to effective sparging design and to the design of the associated SVE system. Various monitoring techniques have been used successfully to determine air flow paths, including neutron probes, time-domain reflectometry, electrical resistivity tomography, and measurement of dissolved oxygen and/or tracer gases such as sulfur hexafluoride or helium in very short-screened monitoring points. Air sparging is often effective at delivering air to the smear zone or capillary fringe, under the right geologic conditions, whereas the high moisture/product content in those zones often prevents adequate remediation by SVE alone.

(2) Injection of gases other than air. Gases other than air can be injected into the subsurface to provide electron acceptors, substrates, nutrients, or tracers. Pure oxygen can be injected as an electron acceptor, but the associated explosion hazard deserves special consideration. Methane (Alvarez-Cohen et al. 1992), propane (Wackett et al. 1989), and natural gas (a mixture of methane, ethane, propane, and traces of larger alkanes) (Wilson and Wilson 1985) can be used as gaseous co-substrates for the biodegradation of trichloroethylene. Again, due to the hazard of explosion, these gases should not be injected at concentrations in air above the lower explosive limit (LEL). Nitrogen can be introduced as a gaseous phase nutrient in the form of ammonia (Dineen et al. 1990) or nitrous oxide. Phosphorus can be similarly provided in the form of triethylphosphate.

(a) In a well-documented application of air sparging and SVE, Hazen et al. (1994) injected carbon, nitrogen, and phosphorus into the subsurface in the form of methane (at concentrations of 1 to 4 percent), nitrous oxide, and triethylphosphate, respectively, at the U.S. Department of Energy (DOE) Savannah

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River Site near Aiken, South Carolina. Helium was also used as a tracer gas to determine if the injected and purged gases were quantitatively recovered, and for a better understanding of flow paths, residence times, and distribution of the gases between the air injection and extraction wells. Further details on the integrated demonstration to remediate trichloroethylene contamination at the Savannah River site, including costs, are included in Schroeder et al. (1992) and LaPat et al. (1999). USACE Kansas City District has used a similar process at a formerly used Department of Defense site in Nebraska.

(b) Tracer gases should ideally be inexpensive, readily available, easily detectable with field instruments, inert, structurally similar to the gases of interest, and not normally present in the subsurface. Tracer studies are used to qualify and quantify the subsurface airflow pathways caused by soil heterogeneities and to validate air permeabilities estimated from air pressure and flux measurements. Tracer gases include sulfur hexafluoride and helium (Marley 1993). A vadose zone tracer gas study involves injecting a tracer gas into the vadose zone at various depths and distances from the vapor extraction well. The extraction well is then monitored for the arrival of the gas, yielding tracer gas travel times in the subsurface. Detailed evaluation of tracer gas test data is described in Moench (1989, 1991) and USEPA (1996).

(c) Sulfur hexafluoride ( $\text{SF}_6$ ) is often used as a tracer. Gas chromatography analysis of  $\text{SF}_6$  using an electron capture detector (ECD) can be accomplished in the field, but analysis is limited to discrete samples, and the radioactive source in the ECD requires a special license. However, inexpensive portable freon meters can be used to continuously monitor sulfur hexafluoride. These meters typically provide qualitative rather than quantitative information on the concentration of sulfur hexafluoride but are appropriate for determining travel times in the subsurface. Sulfur hexafluoride is not likely to be toxic to micro-organisms at low concentrations. Kampbell and Newell (1990) found that minor amounts, such as one percent, of sulfur hexafluoride did not, but a major amount (about 95 percent) did, inhibit biodegradation of n-butane. Helium is inert and convenient to detect using a thermal conductivity detector. Both sulfur hexafluoride and helium have molecular weights which are very different from oxygen and other air constituents; however, this is only important when gaseous diffusion is the predominant transport mechanism, not in situations involving significant advection. Methane has the advantages of low cost and ease of continuous detection using a flame ionization detector; however, methane can be produced or consumed in biological activity and is therefore not inert.

(d) Argon was injected along with air in BV field treatability tests at the Tyndall, Fallon, and Eielson U.S. Air Force Bases and at Naval Air Station Patuxent River to distinguish gaseous diffusion from oxygen consumption by aerobic micro-organisms (Hinchee, Ong, and Hoepfel 1991b). Helium is the recommended tracer gas in the U.S. Air Force protocol for field treatability tests for BV (Hinchee et al. 1992).

(3) Pneumatic/hydraulic fracturing. Soil and rock fracturing has been used for years to enhance oil recovery from low-yielding oil wells. In the context of SVE and BV systems, pneumatic/hydraulic fracturing creates fractures in soil or rock to increase bulk air permeability. The process consists of injecting air or fluids under high pressure into soil or rock until a critical pressure is reached and fractures are formed. This technique is particularly beneficial for improving advective airflow in fine-grained soils such as clays and silts. SVE airflow rates in fractured wells can increase 25 to 40 times over those in unfractured wells (USEPA 1993e). Both vertical and horizontal fractures can be created. The creation of preferential pathways using fracturing will not, however, enhance diffusion-limited transport from low permeability zones removed from direct contact with airflow pathways.

(a) The USEPA Office of Research and Development Risk Reduction Engineering Laboratory and the University of Cincinnati developed a hydraulic fracturing process (USEPA 1991e). The process creates sand-filled horizontal fractures up to 25 mm thick and radiating out from the point of injection as much as 6 meters. A viscous mixture of sand (termed a "proppant"), guar gum gel, enzyme, and water is hydraulically jetted into a borehole using a slurry pump. After injection, the enzyme additive breaks down the injected viscous fluid and leaves open fractures filled with clean permeable sand. These fractures have been placed at multiple depths at as little as 1.5 meters below the ground surface. Fracturing has been conducted in the oil industry to depths in excess of 6000 meters (20,000 feet).

(b) Another soil and rock fracturing process has been developed and patented by the Hazardous Substance Management Research Center (HSMRC) of the New Jersey Institute of Technology. The process pneumatically fractures fine-grained soil and rock by injecting high-pressure air or other gas. The process involves placing a patented air jet nozzle/packer assembly at the desired depth in the borehole and using a compressed air source to create a high-pressure pulse to fracture soil at a selected depth. To maximize the benefits of fracturing, care is taken to position the air jet nozzle/packer assembly in the borehole to ensure that only clay or silt soils are exposed between packers. Since no proppant is inserted into the fractures, they can collapse to some degree, depending on the structural strength and degree of consolidation of the soils adjoining each created fracture.

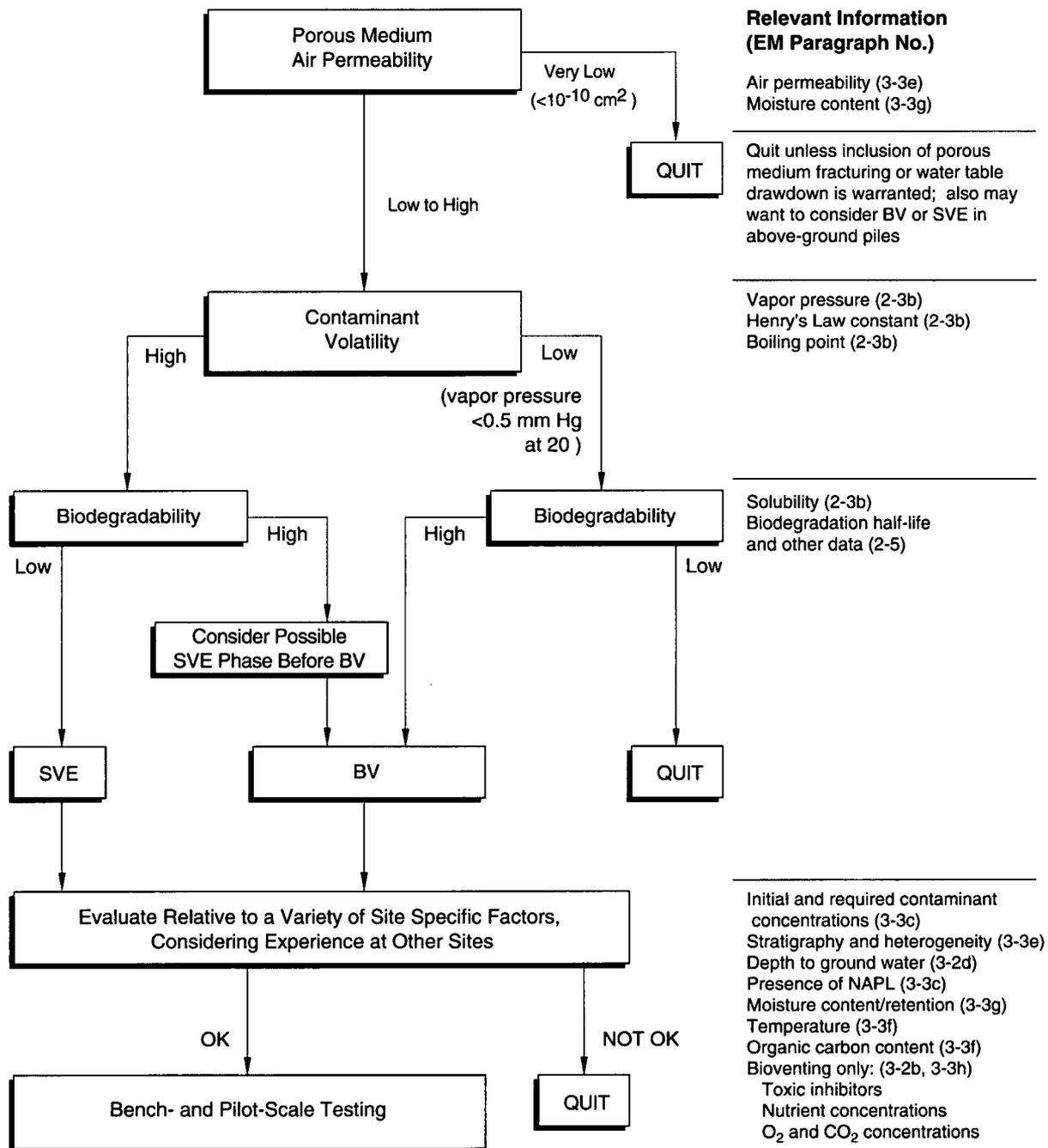
### 3-3. Pre-Design Data Requirements and Technology Screening Strategy

The primary criteria in selecting from the technology options described above are air permeability of the porous medium and volatility and biodegradability of the contaminants. Potential technologies are then further screened with a variety of site-specific factors in mind. This is illustrated in Figure 3-10. A host of other technologies should initially be screened along with technologies involving SVE and BV.

*a. Approach to technologies.* An integrated approach to SVE/BV and other technologies is preferred. For example, SVE/BV may be considered as part of a remediation system that also includes groundwater and product recovery. It is therefore critical that data be collected to address the feasibility of SVE/BV and also other technologies that might potentially be applied at the site.

*b. Site conditions and the Site Conceptual Model.*

(1) Numerous site physical, chemical, and biological conditions have a significant impact on the effectiveness of SVE/BV as a remedial alternative. These parameters are discussed in the sections below, along with site characterization data pertinent to SVE/BV feasibility and design that should be collected. Table 3-1 summarizes these site characterization data. The importance of gathering the pertinent data as early as possible cannot be overemphasized. Although one's understanding of the site will never be perfect (because characterization tools, financial resources, and sampling methods have practical limitations), one has an obligation to assemble and document lines of evidence that *converge* towards a consistent picture of the site. This picture, or conceptual model, of the site is necessarily multi-faceted and multi-disciplinary, in that it encompasses a variety of types of data. It is also dynamic, in that it evolves as additional data become available. It is important to continually reformulate the site conceptual model as new field efforts provide new information.



Source: ENSR, 1994

Figure 3-10. Technology screening decision tree

(2) The conceptual model should describe the source(s) of the contamination, the mass released (if known), the pattern of release (i.e., was the release sudden or gradual? at one or multiple locations?), and particularly the vertical and horizontal extent of contaminant distribution in the vadose zone. There are a number of key aspects to vadose zone characterization for soil venting. In brief, these include: soil type, distribution and depth; depth to water table and its seasonal fluctuation; soil moisture content and variability; thickness of the capillary fringe; air permeability and how it varies within the domain of interest; organic carbon content and variability; type/condition of surface cover (e.g., asphalt, vegetation); presence and extent of buried structures or utilities; and topography. Any one (or a combination) of these key site elements can strongly influence soil venting effectiveness and/or present a serious limitation to soil venting. Often, site characterization data potentially important to application of SVE/BV technologies are not collected because those responsible for logging soil borings and observation pits are either not aware of them or are not prompted to recognize and systematically record them. Understanding the nature of surface horizons are critical and cannot be overemphasized. Indications of subsurface features, such as sandy or gravelly lenses in a finer-textured matrix, or macropores, that might serve as preferential airflow pathways should be logged. Soil colors and mottling can provide an indication of the zone within which the water table seasonally fluctuates. In urban or industrial locations, the contact between disturbed soil/fill and native soil should be discerned if possible. Standard methods of soil characterization should be employed for these purposes by those trained in their use (Breckenridge, Williams, and Keck 1991; USEPA 1991h).

(3) Once a conceptual model is sufficiently advanced to recognize the general nature and extent of contamination and/or source area, remediation can and often should begin. SVE/BV system designers should collect site-specific venting performance data during the design process. Such opportunities often center on SVE and BV pilot tests, but they may also entail shorter field tests such as air permeability tests, or phased SVE system installation and operation. Whatever the duration, each time the designer goes to the field to collect data on system performance much can be learned about the way the site will behave during the remediation itself. (These opportunities must be used judiciously, however, as they demand time and resources to carry out, which should be balanced against the extra expense and time that would be needed were one to end up operating a system at suboptimal effectiveness.) Each new phase of the remediation system is then predicated upon the knowledge gained from the previous phases. Design flexibility is an essential component of this approach – to accommodate design/operational changes. This can be a reason to have the designers of in situ systems also be the installers and operators, in contrast to the more common process of bid specification, contract award, system installation and operation, by firms unrelated to the designers.

(4) An initial phase of remediation or a pilot test (discussed in Section 4.0) should be employed to further the understanding of the site and the applicability of soil venting to remediate the site. The practitioner is encouraged to proceed with phased design and implementation of SVE/BV systems for a variety of reasons.

- In comparison to more traditional engineering projects (e.g., bridge design), the basis for design for subsurface environmental remediation is quite weak, typically based on a limited number of soil samples. This is not consistent with the traditional notions of 30%, 60%, 90% 100% design, common to many engineering projects that are typically predicated on solid, unchanging information.
- Often the very execution of a remediation design (e.g., installation of SVE injection and extraction wells) dramatically increases our site understanding and confidence in the site conceptual model.
- Phased implementation enables the designer to "ground-truth" design assumptions. Pilot tests typically use only a few, or sometimes only one, well/s for extraction; and test duration often

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ranges from a few days to a month. Based on data from such tests, multi-well SVE systems may be designed and implemented. If the resulting system is installed in phases, full-scale operational data can be developed and then used for modifying the design of subsequent system components.

- Off-gas treatment system sizes can be minimized if an extraction system is phased in or staged sequentially, thus limiting the peak concentration and/or peak mass removal rates. Phasing (e.g., bringing a limited number of wells on-line initially) enables purchase of smaller treatment equipment (e.g., thermal oxidizer).

c. *Nature and extent of contamination.* During site characterization, the chemical properties of the site media and the nature and extent of the contamination must be determined in order to evaluate the feasibility of SVE/BV. Contaminants most amenable to SVE are VOCs that include gasoline, kerosene, many diesel fuel constituents, freons, and solvents such as PCE, trichloroethene, and methylene chloride. Table 3-2 lists contaminants for which USEPA considers SVE to be a presumptive remedy per Directive 9355.0-48FS (USEPA 1993a). Table 3-3 presents various contaminant groups and rates their amenability to SVE. The physical and chemical characteristics that make these contaminants amenable to SVE are discussed in paragraph 2-3b.

**Table 3-1. Testing and Analytical Method Summary**

| Parameter   | Collection Method   | Analytical Method  |
|---|---|--|
| Air-phase permeability (field-scale)                          | Pneumatic pump test   | See Cho and DiGiulio (1992)  |
| Air-phase permeability (core-scale)                           | In situ or undisturbed 50- to 75-mm diameter soil sample typical                                  | See paragraph 4-2d and Appendix D; Corey (1986a)   |
| Stratigraphy/heterogeneity                                    | Soil boring and/or test pit   | Visual observation; Breckenridge, Williams, and Keck (1991); USEPA (1991h)                       |
| Grain size  | Split spoon or other soil sample  | ASTM D422-63 (1998)  |
| Porosity  | Undisturbed 50- to 75-mm-diameter soil sample   | Calculated from dry bulk density and particle density  |
| Dry bulk density  | Undisturbed 50- to 75-mm-diameter soil sample   | ASTM D2850   |
| Organic carbon content  | Split spoon sample  | SW-846 9060; Churcher and Dickhout (1989)  |
| Moisture content (saturation)                                 | Neutron logging via access tubes<br>Tensiometers<br>Undisturbed 50- to 75-mm diameter soil sample | Neutron gauge (Gardner 1986), ASTM D3017, ASTM D5220<br>Cassel and Klute (1986)<br>ASTM D2216-92 |
| Soil moisture retention (Capillary pressure saturation curve) | Undisturbed 50- to 75-mm diameter soil sample   | Klute (1986); ASTM D2325-93  |
| Dry end soil moisture retention                               | Undisturbed 50- to 75-mm diameter soil sample   | Psychrometer Method (Jones, Gee, and Heller 1980)  |
| Soil Temperature  | Thermometer, Thermocouple   | Portable Meter   |
| Depth to groundwater and seasonal variations                  | Water table monitoring wells, Water level meter or interface gauge and surveyed well elevations   | ASTM D4750   |
| Volatile hydrocarbon content in soil gas                      | In situ   | Downey and Hall (1994); ASTM D3416-78  |
| O <sub>2</sub> content in soil gas                            | In situ   | Portable meter, electrochemical cell method  |
| CO <sub>2</sub> content in soil gas                           | In situ   | Portable meter, infrared adsorption method   |
| Microbial respiration rate                                    | In situ   | Hinchee et al. 1992  |

**Table 3-1. Testing and Analytical Method Summary**

| Parameter  | Collection Method                | Analytical Method  |
|--|----------------------------------|--|
| Heterotrophic bacterial plate count                      | Split spoon or other soil sample | EPA Method 600/8-78-017  |
| Hydrocarbon degraders                                    | Split spoon or other soil sample | EPA Method 600/8-78-017  |
| pH   | Split spoon or other soil sample | EPA Method 9045B, 9045C  |
| Nitrate/nitrite-nitrogen <sup>1</sup>                    | Split spoon or other soil sample | EPA Method 353.1-353.3; SM4500-N   |
| Ammonia-nitrogen <sup>1</sup>                            | Split spoon or other soil sample | EPA Method 350.1-350.3; SM4500-NH3 A-H                                   |
| Total Kjeldahl nitrogen <sup>1</sup>                     | Split spoon or other soil sample | EPA Method 351.1-351.4; SM4500-Norg A-C                                  |
| Total and ortho phosphorus <sup>1</sup>                  | Split spoon or other soil sample | EPA Method 365.4; SM4500-P A-F   |
| Barometric pressure fluctuations and subsurface response | Barometer and vacuum gauge       | Portable meters, Electronic recorders can be used with electronic meters |

<sup>1</sup> Listed analytical methodologies are for aqueous samples and will need to be modified for soil samples.

(1) The site investigation must also search for the presence of contaminants that are not amenable to SVE, e.g., heavy metals such as lead or cadmium, or polychlorinated biphenyls (PCBs), because remedy selection will depend on an assessment of all the contaminants of concern at the site. Table 3-3 includes examples of the more common chemicals and products that are not amenable to SVE. Their presence at a site will not necessarily preclude the selection of SVE as a partial solution or a component of a treatment train.

(2) The reader should be aware that, over the years, chemicals have often been referred to by numerous synonyms and trade names. Tetrachloroethene (PCE) is synonymous with tetrachloroethylene, perchloroethene, and perchloroethylene, for example. In evaluating historical analytical data or records of the use of chemicals or products, references such as The Merck Index (Merck & Co. 1989) can provide the synonyms of the chemicals or products that are present or were used. Consideration of possible synonyms may also be important in organizing information in electronic databases should the size of the project merit such an endeavor.

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**Table 3-2 . VOCs Considered to be Amenable to SVE**

|   |  |
|---|--|
| <b>Halogenated Volatile Organics</b>    |  |
| Carbon Tetrachloride                    |  |
| Chlorobenzene                           |  |
| Chloroethane                            |  |
| Chloroform                              |  |
| 1,1-Dichloroethane                      |  |
| 1,1-Dichloroethylene                    |  |
| 1,2-Dichlorobenzene                     |  |
| 1,2-Dichloroethane                      |  |
| 1,2-Dichloroethylene                    |  |
| 1,2-Dichloropropane                     |  |
| 1,4-Dichlorobenzene                     |  |
| 1,1,1-Trichloroethane                   |  |
| 1,1,2-Trichloroethane                   |  |
| 1,1,2,2-Tetrachloroethane               |  |
| Ethylene Dibromide                      |  |
| Methylene Chloride                      |  |
| Tetrachloroethylene                     |  |
| Trichloroethylene                       |  |
| Vinyl Chloride                          |  |
| <b>Nonhalogenated Volatile Organics</b> |  |
| Ketones/Furans                          | Acetone<br>Methyl Ethyl Ketone<br>Methyl Isobutyl Ketone                           |
| Aromatics                               | Benzene<br>Ethyl Benzene<br>Styrene<br>Toluene<br>m-Xylene<br>o-Xylene<br>p-Xylene |

NOTE: Other compounds that have physical/chemical characteristics similar to the compounds listed may also be addressed by the presumptive remedy process.

Source: EPA 1993d

**Table 3-3. Effectiveness of SVE on General Contaminant Groups for Soil**

| Contaminant Groups    |                       | Example of Contaminants             | Effectiveness            |
|-----------------------|-----------------------|-------------------------------------|--------------------------|
| <b>Organics</b>       | Halogenated VOCs      | Tetrachloroethene, Trichloroethene  | a                        |
|                       | Halogenated SVOCs*    | Para-dichlorobenzene                | b                        |
|                       | Nonhalogenated VOCs   | Gasoline                            | a                        |
|                       | Nonhalogenated SVOCs* | Diesel fuel                         | a                        |
|                       | PCBs                  | Aroclor - 1242                      | c                        |
|                       | Pesticides            | Chlordane                           | c                        |
|                       | Dioxins/furans        | 2,3,7,8-Tetrachlorodibenzo-p-dioxin | c                        |
|                       | Organic cyanides      |                                     | c                        |
|                       | Organic corrosives    |                                     | c                        |
|                       | Explosives            | 2,4,6 Trinitrotoluene               | c                        |
|                       | <b>Inorganics</b>     | Volatile metals                     | Mercury, tetraethyl lead |
| Nonvolatile metals    |                       | Nickel, chromium                    | c                        |
| Asbestos              |                       |                                     | c                        |
| Radioactive materials |                       |                                     | c                        |
| Inorganic corrosives  |                       |                                     | c                        |
| Inorganic cyanides    |                       | Sodium cyanide                      | c                        |
| <b>Reactive</b>       | Oxidizers             |                                     | c                        |
|                       | Reducers              |                                     | b                        |

a Demonstrated Effectiveness: Successful treatability test at some scale completed.

b Potential Effectiveness: Expert opinion that technology will work.

c No Expected Effectiveness: Expert opinion that technology will not work without enhancements.

\* Demonstrated effectiveness on some compounds in the contaminant group.

Source: modified from U.S. EPA 1991c

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(3) The extent of contamination must be determined in three dimensions during the site characterization phase of the project in order to screen appropriate technologies. With regard to SVE, the unsaturated zone and the saturated zone must both be characterized.

(4) Depth of contamination affects the feasibility and design of SVE/BV systems. If contamination is limited to the ground surface, technologies other than SVE/BV will be favored. If contamination is located at depth in the saturated zone, SVE/BV alone will not be feasible. At sites where SVE/BV is feasible, the depth of contamination will influence well type (horizontal versus vertical), the well interval screened, and other design factors.

(5) The volume of contaminated soil impacts the feasibility of SVE/BV. If the volume is small, other alternatives such as excavation and offsite disposal may be more cost effective. The volume of contaminated soil also impacts many aspects of system design, such as number of wells, size of blowers, and offgas treatment system capacity.

(6) Potential offsite sources of vapor phase contaminants must be considered in determining the feasibility and design of SVE/BV systems. If significant vapor phase contamination could migrate onsite from offsite sources during SVE/BV, system design will need to include air injection wells or some other means of preventing this occurrence.

(7) The site investigator should determine whether NAPL is present. Free product in groundwater samples would be one indication of NAPL. NAPL competes with air and soil moisture for pore space within the unsaturated zone, reducing the air phase permeability. In addition, NAPL provides an ongoing source of contaminants. Unsaturated zone residual saturations of between 15 and 50 percent of available pore space have been reported (USEPA 1989c).

(8) If the presence of DNAPL is suspected, there may be concerns that implementation of SVE/BV could increase rather than reduce the risk of migration of DNAPL into deeper hydrologic units. This might be the case, for example, if DNAPL resides in fractured bedrock above the water table. It has been theorized that inducement of airflow toward an extraction well in such a setting might be accompanied by a counterflow of DNAPL deeper into the fracture system, and perhaps into the saturated zone. A Technical Impracticability waiver might be applicable in such a situation (USEPA 1993g).

(9) At the outset of the project, provisions should be made to develop an integrated approach to data management to improve the efficiency and quality of site analyses. To maximize efficiency, it is critical that appropriate data be collected at the appropriate time. An environmental database can afford greater efficiency and data quality in all aspects of project execution from initial field work to production of final reports. For example, such a system could produce preprinted chain-of-custody forms and labels for the field team and could accept standard electronic deliverable data packages from analytical laboratories. The ability to import chemical data directly from the laboratories significantly improves both efficiency and quality over manual data entry.

*d. Contaminant sampling and analysis methods.* At most sites, samples of vapor, soil, and groundwater will need to be analyzed for a variety of possible contaminants. At some sites, samples of free product (LNAPL or DNAPL) or sludges may also require testing. It is critical that all contaminants be identified and evaluated during site characterization, including compounds of little or no interest to

regulators, because their presence can affect treatment. This includes both onsite contaminants and offsite contaminants that could migrate to the site during SVE/BV.

(1) Much effort has been expended by the USACE, the USEPA, and others in developing documents specifying methods of characterizing sites with regard to contamination. These documents describe in detail the procedures and standards for developing Sampling and Analysis Plans (SAPs), Quality Assurance Project Plans (QAPPs), and Data Quality Objectives (DQOs). The documents set forth excellent general principles for performing work of known quality that satisfies project objectives. These documents are listed below.

(2) Technical Project Planning Process EM 200-1-2, USACE 1998. This manual identifies a process by which project approach is established and the data requirements (quantity, location, and quality) are set. Furthermore, the approach recommends that data collection options be developed, a sampling program be selected based on the optimum use of resources, sampling results collected and data compared to objectives.

(3) SAP: USACE 2001. Requirements for the Preparation of Sampling and Analysis Plans. EM 200-1-3. This manual provides guidance on selecting the most appropriate type of sampling approach (e.g. random or grid sampling), the numbers of samples that should be collected from each medium, and the laboratory analyses that should be performed to achieve program objectives with the desired level of confidence. Information on sampling methodology, laboratory analysis methods, and QAPPs is also provided. Table 3-4 lists the topics covered in the SAP.

(4) USEPA Region 4 1997. Environmental Investigations Standard Operating Procedures and Quality Assurance Manual. This manual describes sampling of environmental media, sample handling and preservation, decontamination of field equipment, installation of monitoring wells, and field quality assurance procedures.

(5) DQO: USEPA 2000. [link to [http://www.epa.gov/quality/qa\\_docs.html](http://www.epa.gov/quality/qa_docs.html)] Guidance for the Data Quality Objectives Process EPA QA/G-4: EPA/600/R-96/055. This document provides general guidance on the DQO development process. The first five steps of the DQO process identify what problem has started the investigation, define the decision statements that the investigation will try to resolve, determine the type of data that will need to be collected to resolve the decision statement, establish when the data will be collected, and develop a decision rule that will define how the decision will be made. The decision rule will define the parameters of interest, specify the action level and will arrive at an "If...then" statement. The sixth step of the process defines quantitative criteria expressed as limits on decision errors that the decision maker can tolerate. The final step is used to develop a data collection design based on the criteria in the first six steps. The DQO process is highly dependent on communication between the appropriate parties (samplers, chemists, engineers, modelers, project managers, QA experts, data users, and decision makers).

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**Table 3-4. SAP Format Requirements**

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Title Page  
Distribution List  
Table of Contents

I Field Sampling Plan (FSP)

Title Page  
Table of Contents

- 1.0 Project Background
  - 1.1 Site History and Contaminants
  - 1.2 Summary of Existing Site Data
  - 1.3 Site-Specific Definition of Problems
- 2.0 Project Organization and Responsibilities
- 3.0 Project Scope and Objectives
  - 3.1 Task Description
  - 3.2 Applicable Regulations/Standards
  - 3.3 Project Schedule
- 4.0 Nonmeasurement Data Acquisition
- 5.0 Field Activities by Area of Concern (AOC)
  - 5.1 Geophysics
    - 5.1.1 Rationale/Design
    - 5.1.2 Field Procedures
  - 5.2 Soil Gas Survey
    - 5.2.1 Rationale/Design
      - 5.2.1.1 Soil Gas Sample Locations
      - 5.2.1.2 Sample Collection and Field and Laboratory Analysis
      - 5.2.1.3 Background, QA/QC, and Blank Samples and Frequency
    - 5.2.2 Field Procedures
      - 5.2.2.1 Drilling Methods and Equipment
      - 5.2.2.2 Materials (Casing, screen, etc.)
      - 5.2.2.3 Installation
      - 5.2.2.4 Sampling Methods
      - 5.2.2.5 Field Measurement Procedures and Criteria
      - 5.2.2.6 Documentation
  - 5.3 Ground Water
    - 5.3.1 Rationale/Design
    - 5.3.2 Monitoring Well Installation
    - 5.3.3 Determine Free Product Presence and Sampling
    - 5.3.4 Aquifer Testing
    - 5.3.5 Field Measurement Procedures and Criteria
    - 5.3.6 Sampling Methods for Ground Water - General
    - 5.3.7 Sample Handling Methods for Ground Water - Filtration
    - 5.3.8 Sample Containers and Preservation Techniques

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**Table 3-4**  
**(Continued)**

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- 5.3.9 Field Quality Control Sampling Procedures
- 5.3.10 Decontamination Procedures
- 5.4 Subsurface Soil
  - 5.4.1 Rationale/Design
    - 5.4.1.1 Soil and Rock Boring Locations
    - 5.4.1.2 Discrete/Composite Soil Sampling Requirement
    - 5.4.1.3 Sample Collection and Field and Laboratory Analysis
    - 5.4.1.4 Background, QA/QC, and Blank Samples and Frequency
  - 5.4.2 Field Procedures
    - 5.4.2.1 Drilling Methods
    - 5.4.2.2 Boring Logs
    - 5.4.2.3 Field Measurement Procedures and Criteria
    - 5.4.2.4 Sampling for Physical/Geotechnical Analyses
    - 5.4.2.5 Sampling for Chemical Analyses
    - 5.4.2.6 Sample Containers and Preservation Techniques
    - 5.4.2.7 Field Quality Control Sampling Procedures
    - 5.4.2.8 Decontamination Procedures
- 5.5 Surface Soil and Sediment
  - 5.5.1 Rationale/Design
  - 5.5.2 Field Procedures
- 5.6 Surface Water
  - 5.6.1 Rationale/Design
  - 5.6.2 Field Procedures
- 5.7 Other Matrices
  - 5.7.1 Rationale/Design
  - 5.7.2 Field Procedures
- 6.0 Field Operations Documentation
  - 6.1 Daily Quality Control Reports (QCR)
  - 6.2 Field Logbook and/or Sample Field Sheets
  - 6.3 Photographic Records
  - 6.4 Sample Documentation
  - 6.5 Field Analytical Records
  - 6.6 Documentation Procedures/Data Management and Retention
- 7.0 Sample Packaging and Shipping Requirements
- 8.0 Investigation-Derived Wastes (IDW)
- 9.0 Field Assessment/Three-Phase Inspection Procedures
  - 9.1 Contractor Quality Control (CQC)
  - 9.2 Sampling Apparatus and Field Instrumentation Checklist
- 10.0 Nonconformance/Corrective Actions

Appendices

A References

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Table 3-4  
(Continued)

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II. Quality Assurance Project Plan (QAPP)

Title Page

Table of Contents

- 1.0 Project Laboratory Organization and Responsibilities
- 2.0 Data Assessment Organization and Responsibilities
- 3.0 DQO
  - 3.1 Data Use Background
  - 3.2 Measurement Quality Objectives for Chemical Data Measurement
- 4.0 Sample Receipt, Handling, Custody and Holding Time Requirements
  - 4.1 Verification/Documentation of Cooler Receipt Condition
  - 4.2 Corrective Action for Incoming Samples
- 5.0 Analytical Procedures
  - 5.1 Preventive Maintenance
  - 5.2 Calibration Procedures and Frequency
  - 5.3 Laboratory QC Procedures
  - 5.4 Performance and System Audits
  - 5.5 Nonconformance/Corrective Actions
- 6.0 Data Reduction/Calculation of Data Quality Indicators
  - 6.1 Precision
  - 6.2 Bias
  - 6.3 Sample Quantitation/Reporting Limits (Limit of Detection)
  - 6.4 Completeness
- 7.0 Laboratory Operations Documentation
  - 7.1 Sample Management Records
  - 7.2 Data Reporting Procedures
  - 7.3 Data Management Procedures
- 8.0 Data Assessment Procedures
  - 8.1 Data QC Review
  - 8.2 Data Verification/Validation
  - 8.3 DQO Reconciliation
  - 8.4 Project Completeness Assessment

Appendices

- A References
- B Standard Forms to be Used
- C List of Abbreviations and Acronyms

Example List of Tables  
Data Quality Objectives Summary  
Site Remedial Objectives

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**Table 3-4  
(Concluded)**

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Previous Analytical Data Summary  
Current Efforts Sampling and Analysis Summary  
Names and Addresses of Owners of Property Near the Site  
Sample Container Quantities  
Proposed Monitoring Well Information  
Sample Container Preservation and Holding Time Requirements  
Summary of Sample Matrices and Locations  
Summary of Number of Samples and Analyses

Example List of Figures

Site Location  
Project Organization  
Proposed Monitoring Well and Onsite Sample Locations  
Proposed Offsite Sample Locations  
Monitoring Well Construction  
Investigation Schedule

Source: EM 200-1-3

Note that outline for sections not as relevant to SVE and BV design have been collapsed to major headings only

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(6) DQO: USEPA 2000. Data Quality Objectives Process for Hazardous Waste Site Investigations. Final Guidance. EPA/G-4HW. This document describes the application of the DQO process to hazardous waste sites.

(7) USACE 1997. Chemical Quality Assurance for HTRW Projects. EM 200-1-6. This manual provides guidance for implementation of analytical chemistry aspects of the USACE HTRW QA program. Includes suggestions for establishment of quality control and quality assurance protocols needed to ensure fulfillment of chemical quality requirements in support of project specific data quality objectives.

(8) USACE 1998. Technical Project Planning (TPP) Process. EM 200-1-2. This manual provides guidance on utilizing the TPP process at hazardous, toxic, or radioactive waste sites. The TPP process involves identifying the project objectives, compiling all data needs for various purposes, developing data collection programs, and preparing DQO statements for compilation into a scope of work. Guidance on implementing and assessing data collection programs is also included.

(9) QAPP: USEPA 1998. Guidance for Quality Assurance Project Plans. EPA/600/R-98/018. This document provides guidance for preparing QAPPs for environmental data collection programs. The guidance addresses each of the QAPP elements as grouped by function: project management, measurement/data acquisition, assessment/oversight, and data validation and usability.

(10) QAPP: USEPA 1999. EPA Requirements for Quality Assurance Project Plans. Interim Final Guidance. EPA QA/R-5. This guidance sets requirements for QA Project Plans prepared for activities conducted by or funded by EPA.

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(11)FSP: USEPA 1993. Subsurface Characterization and Monitoring Techniques, A Desk Reference Guide [EPA 625/R-93/003]. This document provides brief descriptions, advantages and disadvantages, and references for more detailed information on a extensive list of techniques of subsurface characterization including soil and soil gas.

(12)The SAP will specify the number and location of samples to be collected and analyzed. There are several different approaches to determining sample locations, including random sampling, stratified random sampling, grid sampling, hot spot sampling, judgment-based sampling, and others. These strategies are discussed in guidance documents listed below. Considerations for soil and groundwater sampling also can be applied to vapor sampling.

(13)If a random, stratified random, or grid-sampling strategy is selected, then the minimum number of samples to be collected must first be determined. The number of samples will depend on the allowable margin of error, the sample variance, the relative sample variance, the desired confidence level of the result, and the precision of the sampling and laboratory methods. These parameters vary depending upon the phase of the project, the area under study, and the parameters being tested. For example, during a field soil gas survey, the margin of error, desired confidence level, and precision of measurements may all be less rigorous than when the site is being evaluated for compliance with cleanup standards. A tool to assist in this approach is the Visual Sampling Plan software developed by Battelle Pacific Northwest National Lab.

(14)Extensive research has been done on the various techniques of collecting water and soil samples and the effects those techniques may have on sample integrity, especially with regard to VOCs and metals. The method best suited for a given site is dependent on expected analytes and concentrations, the number of locations to be sampled, and trade-off considerations of cost versus convenience. For example, if groundwater samples will be collected frequently from the same well, dedicated pumps or bailers may be appropriate. However, the collection of soil samples for VOCs must be performed as described in SW-846 Method 5035 (USEPA 1986). Samples should be collected for low-level (acid solution preservation) and/or high-level (methanol preservation) analyses depending on the data quality objectives (e.g., required detection limits). Guidance on the collection of samples by this methodology can be found in the Interim Chemical Data Quality Management (CDQM) for USACE Hazardous, Toxic and Radioactive Waste (HTRW) Projects (USACE, 1998) and Chapter 3 of the Multi-Phase Extraction Manual (EM 1110-1-4010).

(15)Soil contaminant concentrations are often remarkably heterogeneous. In some situations, it is appropriate to composite soil samples so that more aliquots of soil can be represented in fewer analytical tests, thus reducing analytical costs. Compositing is inappropriate for light solvents and VOCs because compounds volatilize and are lost from the sample during mixing, but compositing may be acceptable for nonvolatile compound analyses. For C12 to C17 diesel, compositing may result in the loss of 10 to 20 percent of the diesel mass.

(16)Air (vapor) samples are collected and analyzed in a number of different ways. Guidance on air sampling and analysis techniques is provided in the following documents:

- National Institute for Occupational Safety and Health (NIOSH) 1984. *Manual of Analytical Methods*. Third Edition. February 1984.
- 40 Code of Federal Regulations, Part 60, Method 18, 1997.

- USEPA 1999. *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*. EPA/625/R-96/010b
- USEPA 1988b. *Field Screening Methods Catalog*. EPA/540/2-88/005.
- Hewitt, A.D., *Establishing a Relationship Between Passive Soil Vapor and Grab Sample Techniques for Determining Volatile Organic Compounds*, US Army Corps of Engineers, September 1996.
- American Society for Testing and Materials (ASTM) 1993. *Standard Guide for Soil Gas Monitoring in the Vadose Zone*. ASTM D 5314-93.

(17) Some commonly used techniques for analysis of VOCs in air samples are:

- Direct injection into a gas chromatograph (GC) equipped with a flame ionization, photoionization, electron capture, or other appropriate detector.
- Adsorption onto Tenax, charcoal, Ambersorb, and/or other appropriate sorbent material(s), followed by GC or GC/mass spectrometry (GC/MS) analysis.
- Cryogenic trapping followed by GC analysis.
- Collection in specially treated canisters followed by GC/MS analysis.

(18) By their very nature, contaminants that are amenable to SVE are amenable to being measured during soil gas surveys. Frequently, field soil gas measurement is a useful way to characterize the nature and extent of soil contamination at a site. Often field measurements of soil gas contaminant concentrations confirmed by a limited number of laboratory analyses are sufficient for site characterization. However, a good quantitative correlation between soil gas and soil concentrations can seldom be obtained. This is particularly true when higher concentrations of contaminants are present due to residual NAPL. When contrasting soil gas and soil sample concentrations it is helpful to keep in mind that soil sample results represent contaminants in all soil compartments (NAPL, dissolved, sorbed, and vapor phases), while soil gas measures only those in vapor. USEPA 1988b and USEPA 1991g above provide guidance on soil gas survey methodology. Soil gas surveys can also provide an indication of contaminant concentrations that can initially be expected in SVE offgas. Long-term offgas contaminant concentrations, however, are not well predicted by soil gas surveys.

(19) Soil gas surveys are instrumental in determining BV feasibility (Downey and Hall 1994). High vapor phase contaminant and carbon dioxide concentrations coupled with low oxygen concentrations may indicate that biodegradation is occurring but is oxygen-limited. These conditions would support further consideration of BV as a remedial alternative. Soil gas surveys can also locate areas with heaviest contamination in which venting wells might be situated.

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(20) Soil gas surveys can be more economical than traditional drilling and soil sampling techniques. However, soil gas monitoring is often impossible in very moist soils, particularly in fine-grained units. Interference from leaked ambient air may lead to erroneous results in such situations. Soil gas surveys of deep units may also be difficult due to soil heterogeneities such as clay layers. Gaseous diffusion in the subsurface, particularly along high permeability conduits such as utility lines, can lead to high soil gas concentrations in areas at some distance from the true source area. Furthermore, the nature of the surface covering and recent precipitation events can affect observed soil gas concentrations. Tight surface coverings can result in high concentrations over wide areas surrounding a release due to limited escape of contaminant vapors to the atmosphere and recent precipitation events can displace contaminant vapors downward and draw in clean atmospheric air into the subsurface.

*e. Air permeability.* Air permeability, the ability of soil to permit the passage of air, is one of the most critical parameters affecting SVE/BV feasibility and design. It is a function of solid matrix properties and moisture content. A number of investigators (Brooks and Corey 1964; Van Genuchten 1980; Mualem 1986) have developed equations to estimate this value from pressure-saturation, bulk density, and saturated hydraulic conductivity data (paragraph 2-3c).

(1) Air permeability has a profound influence on airflow rates and contaminant recovery rates. Coarse-grained soils typically exhibit large values of air permeability and more uniform airflow patterns. Both of these factors tend to promote increased contaminant recovery rates. By contrast, fine-grained soils are characterized by small values of air permeability and airflow patterns that are primarily restricted to macropores or secondary permeability zones such as fractures. This results in increased removal of contaminants from these zones; however, at distances away from these high permeability zones, where residual contaminants may be bound in a fine-grained matrix, recovery rates are reduced (Johnson et al. 1994). In these cases, air permeability should be measured in the field to more realistically assess the influence of macro-features (secondary flow features). Air permeability of fractured rock is highly variable based on the degree and interconnections existing between fractures. If the fractured rock is also porous or if the contaminant has been present in the fractures over a long period, significant contaminant mass may reside in the rock matrix. In this case, diffusion may be a dominant process in removing mass from the rock matrix. Air permeability can be measured or estimated by a variety of methods, several of which are presented in paragraphs 4-2a and 4-5 and in Appendix D. Soils with air permeabilities less than about  $10^{-10}$  cm<sup>2</sup> may not be amenable to SVE/BV (USEPA 1993d).

(2) As mentioned before, moisture is a primary determinant of air permeability, and is held at higher saturation levels in fine-grained soils than coarse-grained soils. Plastic fine-grained soils, moreover, if dried to the point of overconsolidation and cracking to form secondary flow features, have been observed on a macro-scale to exhibit air permeabilities comparable to fine- to medium-grained sands. The designer needs to assess the appropriateness of soil sample derived properties (such as permeability) in cases where macro-features may dominate.

(3) Heterogeneities play a significant role in the distribution of contaminants within the unsaturated zone and are caused by spatial variations in soil type, layering, porosity, and moisture content. During the operation of an SVE/BV system, these variations may influence airflow patterns and ultimately contaminant recovery rates within the unsaturated zone. For example, if the unsaturated zone is comprised of alternating layers of coarse- and fine-grained soils, airflow may be restricted to the coarse-grained strata. Contaminants are often removed from the finer grained strata at much slower rates. Soil borings, cone penetrometry, and soil profile examinations of the exposed faces of test pits are among the methods to obtain information on physical heterogeneities.

(4) In some instances, underground utilities such as storm and sanitary sewers or the backfill material associated with these features may produce short-circuiting of airflow associated with an SVE/BV system. As a result, airflow may be concentrated along these features rather than within the zone requiring treatment. In addition, these features may also provide migration pathways for both free-phase liquids and vapors within the unsaturated zone. As a result, the orientation and geometry of these features may dictate the direction in which the liquids or vapors migrate. Often, accurate as-built drawings of underground utilities do not exist, so persons familiar with the site should also be consulted. Basements of nearby buildings and other features that may affect flow should be noted.

(5) Topography and the nature of the ground surface will affect SVE/BV. An impermeable surface will tend to enhance horizontal airflow and increase the radius of influence. A permeable surface will do the opposite and will increase the amount of atmospheric air entering the subsurface. Surface constraints such as buildings, roadways, and utility systems may make SVE/BV an attractive remedial alternative relative to other options. If pavement is present at the ground surface, its integrity should be examined. Any cracks should be noted and, if possible, sealed (see paragraph 5-16).

*f. Solid matrix properties.* Data on solid matrix properties (introduced in paragraph 2-3c) should be collected during site characterization. Grain size analyses provide information on the distribution of particle sizes in a soil. Typical porosities for sands and gravels are 25 to 40 percent. Porosities for fine-grained soils are higher, typically 35 to 50 percent for silts and 40 to 70 percent for clays (Freeze and Cherry 1979). Porosity can be calculated from measurements of bulk density using Equation 2-4.

(1) The subsurface temperature significantly influences the vapor pressure of a given compound. As the temperature increases, the vapor pressure increases. Jury et al. (1987) reported that for intermediate weight organic compounds, the vapor pressure may increase as much as four times for each 10°C increase in temperature.

(2) The fraction of organic carbon in a soil (*foc*) affects the ability of a given compound to partition to the gaseous or aqueous phases. Soils characterized by high *foc* values have a tendency to limit the amount of mass that partitions from a soil particle to the surrounding pore space. In contrast, soils characterized by low *foc* values tend to promote such partitioning.

*g. Water.* The moisture content of a soil influences the magnitude of the air permeability. Water competes with air and NAPL to occupy pore space within the soil and ultimately reduces the ability of vapors to migrate through the unsaturated zone due to a reduction in air pathways.

(1) In addition, moisture content has a significant impact on gas phase partitioning. Farmer et al. (1980) and Aurelius and Brown (1987) have demonstrated that volatilization decreases as the soil approaches full water saturation. By contrast, based on work nearer the dry end of the moisture spectrum, Lighty et al. (1988) and Houston, Kremer, and Marwig (1989) reported that adsorption of VOCs to soil increases as the water content decreases. This was attributed to the fact that when some moisture is present, water molecules compete for the same adsorption sites as the contaminants. As a result, water molecules displace the contaminants from the soil surface for subsequent transport by SVE. In summary, while low water saturations favor higher relative air permeabilities, desiccated conditions retard desorption of VOCs and should be avoided (USEPA 1991d). Desiccation can be prevented by passing the injection air through a humidification unit. Moisture content in soil samples can be measured gravimetrically. Moisture

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content can also be monitored in situ by a variety of methods, including tensiometry, neutron thermalization, and time domain reflectometry (Baker and Wiseman 1992).

(2) The unsaturated hydraulic conductivity and the air permeability of a soil are functions of its moisture content. As a result, under various levels of soil vacuum (i.e., pressures less than atmospheric), the moisture content, as well as the unsaturated hydraulic conductivity and air permeability will change (Hillel 1980a). Capillary pressure-saturation (i.e., soil moisture retention) measurements enable one to quantify the ability of a soil to retain moisture under a specific vacuum condition and consequently to predict the effects of pressure and saturation on air permeability (Baker and Wiseman 1992). The tests may be considered as a measure of the storage capacity (i.e., the air-filled porosity) of a soil at a specific equilibrium vacuum. They indicate whether the soil exhibits a distinct air-entry suction and its value. They also provide an indirect measure of the pore size distribution, which more directly affects SVE than does the grain size distribution. Methods of measuring capillary pressure-saturation are given in Table 3-1.

(3) Moisture content is also important for bioventing applications. Since most if not all of the degradation occurs in the water phase, if the moisture content drops below a threshold, biodegradation will diminish significantly. For bioventing, moisture content should be between 5% and 20% (Downey 1995). In application of passive bioventing to soils at Kirtland AFB, New Mexico, Johnson and others found that moisture was the limiting factor for bioventing and supplemental moisture and nutrients were added in the vapor-phase (Johnson et al 1999). If moisture content is too high, water will occlude pore spaces and prevent movement of air (i.e., oxygen) into the soils. Insufficient oxygen levels will, in turn, reduce the rates of biodegradation.

(4) Humidity is important in SVE and BV. Water vapor, like liquid water, enhances desorption of contaminants from soil particles. Davies (1989) states that the critical moisture regime for SVE applications is in the range of 94 to 98.5 percent relative humidity in the soil gas. Below this range, VOCs are more tightly bound to soil and may not volatilize as readily.

(5) The water table surface acts as a no-flow boundary for airflow and is used to define the thickness of the vadose zone. Subsequently, the depth to groundwater as well as seasonal variations need to be evaluated, in part to ensure that the SVE/BV system will not be flooded during a high water table period.

*h. Microbiology.* Concentrations of electron acceptors, such as oxygen, and respiration byproducts, such as carbon dioxide and methane, can provide an indication of whether biodegradation is naturally occurring in the subsurface. Where oxygen is depleted, forced air may be used as an oxygen source to promote aerobic microbial biodegradation within the unsaturated zone. One advantage of introducing oxygen as a gas phase is that gases possess greater diffusivities than liquids (Hinchee et al. 1992). As a result, gas phase oxygen can be delivered much more rapidly (i.e., at rates several orders of magnitude greater) than oxygen delivered in the liquid phase. Secondly, the oxygen concentration in the gas phase (approximately 21 percent in air) is much greater than the oxygen concentration that can be delivered in the aqueous phase (about 0.0008 percent in aerated water).

(1) In contaminated soil, a variety of heterotrophic and specific hydrocarbon degrading bacteria are often present. These bacterial populations may be limited by electron acceptors (e.g., oxygen), electron donors (e.g., organic matter) and nutrients (principally nitrogen and phosphorus). In the case of fuel-contaminated soil, the populations are usually limited by the availability of the electron acceptor (i.e., oxygen). If BV is a possible candidate remediation technology for a site, and conditions exist (e.g.,

extremes of pH, elevated heavy metals concentrations) that raise doubts as to the viability of the indigenous microbial community, it is advisable to screen soil samples for microbial activity. High bacterial populations in soil can be indicative of conditions that should accommodate bioremediation. Low populations do not necessarily mean that bioremediation is not feasible but may indicate that toxicants, or other factors, are suppressing microbial activity. If the number of aerobic bacteria increase after bioventing is initiated, or increase compared to a control area not being biovented, it can indicate that conditions supporting microbial activity have improved through bioventing. The heterotrophic plate count, formerly known as the standard plate count, is a procedure for estimating the number of live aerobic heterotrophic bacteria in water and wastewater. The method can also be adapted for soil samples. Plates (petri dishes) containing a medium of food and nutrients (usually nutrient rich agar) are inoculated with the soil or groundwater sample. The plates are incubated for about one week, during which time colonies arise from pairs, chains, clusters, or single cells, all of which are counted and included in the term "colony-forming units (CFU)." The results are typically expressed in exponential numbers, such as  $2 \times 10^6$  CFU/g-soil. Several bacterial enumeration methods (including pour plate, spread plate, most probable number (MPN) tubes and the membrane filter method) and different media are described in APHA/AWWA/WEF (1992) and Soil Analysis, Part 2, Chemical and Microbiological Properties, 2<sup>nd</sup> Edition (Page et al, 1982). The numerical results from different enumeration methods may not be directly comparable. Therefore the same method should be used to evaluate different areas of the site of conditions over time. The spread plate method is often used for bioremediation monitoring and is routinely performed by commercial laboratories. These methods can also be adapted to counting specific contaminant degraders in contaminated zones by using a medium that contains one or more of the organic contaminants from the site as the sole carbon source. Observing these numbers increase or being greater in the treatment area than in background, non-contaminated areas, could also be interpreted as evidence of stimulated bioremediation. While bacteria counts alone provide only an indirect, and rather imprecise measure of the useful biological activity at a site, when coupled with corroborating data such as measurements of respiration rate and moisture and nutrient levels, they may aid in the interpretation of trends in BV performance. Published and measured bacteria count values are site specific and can vary greatly, and thus care should be used in comparing data between sites. Increased bacterial numbers could also be due to stimulation of the biodegradation of naturally occurring organic matter and not the contaminants of concern.

(2) Other methods of estimating the number of soil bacteria include phospholipid fatty acid analysis, enzyme activity analysis, and ATP bioluminescence assays. The assessment of microbial activity under actual field conditions can also be elucidated during the site assessment process through the measurement of soil gas oxygen and carbon dioxide concentrations during soil gas survey activities. Depressed oxygen and elevated carbon dioxide levels throughout the site relative to background levels provide evidence of field microbial viability.

(3) Soil samples should be tested for pH to determine whether conditions are too acidic or alkaline to support abundant microbial populations. pH also provides a basis for assessing the likelihood that CO<sub>2</sub> will be generated as a result of aerobic degradation, and whether this gas should be monitored. Optimal pH is generally in the range of about 6 to 8. Soil samples should also be examined for concentrations of macronutrients, specifically nitrogen (N) and phosphorus (P). Deficiencies in available N and/or P may limit microbial populations and activity. In such cases, amending the soil with nutrients may lead to increased biodegradation rates. Analyses for nitrate/nitrite-N and ammonia-N provide a measure of the N which is readily available to microorganisms, while total Kjeldahl N (TKN) measures the total pool of organic N plus ammonia in the soil, comprising both readily available and less available N (such as that in biomass proteins). Similarly, ortho P indicates the concentration of readily available P, while total P includes less available forms of P.

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(a) A review of over 60 U.S. Air Force pilot- and full-scale BV projects concluded that natural nutrient levels have been sufficient to sustain some level of biological respiration at all sites when oxygen is provided (Miller et al. 1993). TKN at the sites ranged from <50 to >700 mg/kg. Lower TKN concentrations were more common; about one-third of the sites had TKN concentrations less than 50 mg/kg. Total P concentrations also ranged from <50 to >700 mg/kg. Sites were more evenly distributed throughout this range. It was noted that a C:N:P ratio of 250:10:1 is optimal, though not necessarily required.

(b) Another review of Air Force BV experience concluded that natural nutrient levels as low as 20 mg/kg TKN and 3 mg/kg total phosphorus have been sufficient to sustain biological respiration when oxygen is provided (AFCEE 1994).

*i. Regulatory constraints and objectives.* The regulatory context under which SVE/BV is performed may depend on the input and approval of several government agencies. While primacy for regulatory oversight usually rests with the state in which the site is located, the USEPA will also be involved if the site is on the National Priorities List (NPL) or if excavation of constituents listed under the Resource Conservation and Recovery Act (RCRA) is required. In addition, sites near surface water bodies may also be under Coast Guard jurisdiction. Sites in or near wetlands may also be subject to local wetland regulation. Care must be taken to ensure that all of the relevant agencies involved are satisfied with the remedial approach and design.

(1) Regulatory cleanup standards are central to SVE/BV feasibility and system design. Cleanup requirements may be too stringent for SVE/BV to be feasible. If SVE/BV is feasible, cleanup standards will impact the duration of remediation, offgas treatment requirements, and other variables.

(2) Sometimes, the only permit required for an SVE/BV system installation and operation is a well permit. However, the SVE system will produce an air stream which may require treatment prior to discharge to the atmosphere, thus in many states an air discharge permit will be required. State air treatment requirements vary widely and may be site-specific; therefore, contact the state directly or through the customer to determine permit requirements.

(3) In many cases, including the regulatory agency representatives in the project planning process (refer to EM 200-1-2) for site characterization, pilot testing, etc. will expedite the implementation of the regulatory approval project and provide information that answers questions important to those agencies without additional mobilization to the field.

*j. Customer's objectives.* The SVE/BV screening process is driven largely by technical and regulatory issues. However, the customer's objectives and preferences should also be incorporated into the remediation plan.

(1) An area where the customer will have concern is in project cost. One method of cost control is extension of the project schedule to spread out capital costs over a longer time period, with annual costs comprising a larger portion of overall project costs. This tactic of amortizing capital costs over a longer time period is especially appealing to customers who operate on strict annual budgets. The customer can also influence project cost and schedule by requiring that field work take place in times of moderate climate, as extreme weather conditions generally increase the cost and time required for field activities. Future land use anticipated by the customer is another consideration. A customer may prefer to exceed

minimum cleanup requirements to enable a site to be used for a particular purpose once remediation is complete.

(2) Other customer concerns may include site access and minimizing disruption of ongoing site operations. Finally, in the interest of community relations, the customer may wish to incorporate aesthetic considerations (such as landscape improvement and noise mitigation) into the remediation design.

*k. Cost as a component of technology screening.* A comparison of the costs of SVE/BV and other technologies can be used to eliminate options which are not economical. At NPL sites, the required level of accuracy of technology screening cost estimation is precisely defined during the Feasibility Study process. At other sites, the level of accuracy may be defined more by customer needs than regulatory requirements. It is essential that the level of accuracy and the comprehensiveness of the technology screening cost estimate be similar for each technology so that the comparison is valid. In addition, a net present value analysis should be performed to allow comparison of alternatives with different design lives and cash flow schedules. The technology screening cost estimate is similar to the feasibility estimate described in Chapter 10. Refer to Chapter 10 and ER 1110-3-1301 for guidance on cost estimating.

### **3-4. Examples of Screening-Level Evaluations of SVE/BV**

Screening level evaluations take place at the technology review stage. Several examples of screening-level evaluations of SVE and BV are described below.

*a.* A site in Puerto Rico was contaminated with a variety of solvents from leaking tanks, primarily methylene chloride, acetone, methyl isobutyl ketone, and xylenes. Methylene chloride DNAPL was present in one confined area. Soil contamination extended to 4.5 to 6.0 meters below the ground surface. Site soils were heterogeneous sand and silt fill in the contaminated area, surrounded by clay. The water table was about 3 meters below the ground surface, and zones of perched groundwater were also present between 1 and 3 meters. SVE and BV alone were ruled out primarily because of high groundwater elevations. Another problem with SVE was that some of the volatile contaminants (e.g., acetone and ketone) were highly soluble and therefore tend to partition more to the aqueous than the vapor phase. The selected remedy was SVE/BV in conjunction with groundwater extraction, steam injection, and biostimulation by nutrient addition.

*b.* A wood-treating NPL site in the southeastern United States was contaminated with high concentrations of polynuclear aromatic compounds, arsenic, and lead. Soils were heterogeneous sands and silts, and the water table was 1.0 to 1.5 meters below the ground surface. SVE was ruled out because the contaminants were not very volatile. BV was ruled out primarily because of high groundwater elevations.

*c.* As mentioned in paragraph 2-3c, laboratory studies of soil samples yielding capillary pressure-saturation curves (also known as moisture retention curves) can provide useful screening level information on the feasibility of SVE/BV. These laboratory evaluations are particularly useful for borderline sites having medium- to fine-grained moist soils. Qualified geotechnical laboratories can test soil samples for pressure-saturation data, and some can model the data points to provide a pressure-saturation curve which indicates the air entry suction. The curves are typically constructed by fitting a Brooks and Corey (1966) or Van Genuchten (1980) function to the data (see paragraph 2-3c). The air entry suction can then be compared with pressures that can economically be applied at a site to screen the site for the feasibility of SVE/BV.

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*d.* Capillary pressure-saturation studies in the laboratory and SVE pilot studies in the field have been conducted in parallel at three sites, including a site with an area of sand and an area of finer-grained soils (Baker and Wiseman 1992) and in a saprolite (Baker and Bierschenk 1995). In all cases, agreement of the laboratory and field data was good. These data suggest that if a careful pressure-saturation laboratory study indicates that SVE/BV is infeasible at a site, a pilot study will likely yield the same conclusion. If the laboratory data indicate SVE/BV is feasible, a pilot study in the field should then be conducted to examine possible preferential flow pathways. This screening approach can allow the feasibility of SVE/BV to be determined in a cost-effective manner for sites with finer-grained moist soils. The importance of understanding the relationship between pressure-saturation relationships and the feasibility of SVE is illustrated by the following example: SVE was selected as the remedy at a Superfund site in New England. The soils were largely silty clays. Although laboratory air-permeability testing suggested adequate permeability to achieve some mass removal, field testing did not achieve significant air flow at many locations. Further work demonstrated that moisture content was high and the water was held by large capillary forces that SVE could not overcome.

*e.* Between 1992 and 1995, the U.S. Air Force applied BV technology at over 125 sites at 50 Air Force installations, located in all 10 USEPA Regions and in 28 states (Miller et al. 1993; AFCEE 1994a). These sites were selected from the universe of Air Force sites using the following screening criteria:

- Petroleum hydrocarbons were to be the primary contaminants, although the additional presence of detectable chlorinated solvents was acceptable.
- Soils were to be permeable to air - sandy soils were preferable, but less permeable soils were also acceptable because the Air Force desired to study a wide range of soil types in the BV initiative.
- The water table was to be at least 1.5 meters below grade, so that dewatering would be unnecessary.
- No significant amount of free product was to be present, although a sheen was acceptable.

Approximately 70 percent of the sites contain greater than 25 percent silt and clay fractions. Out of 117 test locations selected with the above criteria and tested by January 1994, BV was infeasible at only 3 locations, due to a combination of high water tables, high moisture content, and fine-grained soils (Miller et al. 1993; AFCEE 1994a).

*f.* The U.S. EPA and the U.S. Coast Guard (USCG) carried out an 18 month-long joint demonstration of in situ remediation of a JP-4 jet fuel spill at the USCG Support Center, Elizabeth City, North Carolina (Cho et al., 1997). The remediation approach for this site was combined SVE/BV following de-saturation of "smear zone". To document actual removal of hydrocarbons, core samples were collected and analyzed for total petroleum hydrocarbons (TPH) in August 1992 prior to air injection and SVE, and in September 1994 following the demonstration. From the difference in soil concentrations measured between the two core sampling events, approximately 2,000 kg of the TPH, 55% of the original mass, was removed. The initial goal of reducing the TPH concentration in soil to < 100 mg/kg was not attained. Monitoring of SVE off-gas revealed that about 1,700 kg of hydrocarbon vapor was collected through the SVE system, accounting for 85% of the actual removal, and leaving only 300 kg hydrocarbon attributable to enhanced

biodegradation. However, biodegradation rates estimated from the rates of O<sub>2</sub> uptake measured during four in situ respiration tests (ISR - described in Chapter 4) conducted between 7 and 18 months after startup ranged from 0.72 to 13.9 mg hydrocarbon/kg soil/day (mg/kg/d), with an overall average of ~3 mg/kg/d. Assuming that 3 mg/kg/d was representative of the entire 18 month-long demonstration period, the total estimated removal by biodegradation over the period is >1,600 kg, nearly equal to the mass collected by SVE. Cho and coworkers (1997) concluded that the demonstration did not achieve mass balance. The estimates of mass removed by SVE combined with BV was greater than the amount actually documented by analyses of cores. Since the amount removed by SVE was based on direct measurement of offgas, while the amount removed by BV was estimated from indirect measurements of O<sub>2</sub> uptake, they concluded that the BV estimates were invalid. They offered possible explanations of inaccurate O<sub>2</sub> uptake measurements due to channeling, or overestimation of biodegradation due to oxygen consumption during chemical oxidation of reduced sulfur and iron minerals that may have formed from anaerobic microbial activity. Even so, they suggested that biodegradation would play an increased role compared to physical removal by SVE as the mass of volatile components diminished.

## Chapter 4 Bench- and Pilot-Scale Testing for SVE and BV

### 4-1. Introduction

In order to determine the overall effectiveness of SVE/BV at a particular site, bench- and/or pilot-scale treatability studies should be performed prior to full-scale design and operation of the SVE/BV system.

### 4-2. Uses of Bench- and Pilot-Scale Testing in Remedial Design

The use of bench- and/or pilot-scale testing can assist the engineer or scientist in determining if SVE or BV is an appropriate means to remediate a site. Bench-scale tests include microcosm and column studies. (Note that the use of microcosm, column, and field tests for BV applications is addressed in paragraph 4-2g.) Pilot-scale tests usually measure pressures, flow rates, contaminant concentrations, and other parameters during air pumping tests. Even if bench-scale tests are performed, it is recommended that a pilot test be performed at the site as an appropriate means to gather important design information and to determine field-scale air-flow behavior.

*a. Column tests to determine design parameters.* Ball and Wolf (1990) recommend column tests in the laboratory for determining design parameters for SVE systems addressing single contaminants in homogeneous isotropic soils at small sites. (They did not consider BV to be applicable to their site.) Their approach is to pack a column with site soil, apply a representative airflow, and measure effluent contaminant concentrations as a function of the number of pore volume exchanges. An exponential decay equation is then fit to these data, and the calibration parameter is used in a scaled-up prediction of the emission rate for the full-scale SVE system. With this information, total soil remediation time and cost can be estimated (see paragraph 4-7a for an example of a bench-scale column study).

*b. Column tests to determine SVE effectiveness.* USEPA (1991c) recommends column tests for remedy screening when there is some question as to whether SVE will be effective at a site. This step may be skipped when the vapor pressure of the target compounds is 10 mm Hg or greater. Column tests are also not feasible for sites with fractured bedrock or heterogeneous fill consisting of large pieces of debris. These studies are relatively low in cost and involve passing about 2,000-pore volumes of air through the column (during about 6 days of operation). USEPA states this is equivalent to the volumetric throughput of air during roughly 3 to 6 years of SVE operation in the field (USEPA 1991c). It should be noted that this equivalence depends on soil conditions such as permeability and moisture content. For instance, in a dry, sandy soil, the 2,000-pore volumes could be removed in as little as one year, while a moist, silty clay could require more than 6 years. In most cases, however, site-specific flow scenarios would fall somewhere in the 3- to 6-year range.

(1) The reason for conducting column tests is to study the diffusion kinetics of the soil. It has been found that contaminant release nearly always becomes diffusion-limited within the first 1,000-pore volumes, indicating that equilibrium is reached relatively quickly. A 2,000-pore volume study period therefore allows diffusion kinetics to be quantified. (Personal Communication w/Evan Fan, USEPA Risk Reduction Engineering Laboratory, Edison, NJ.)

(2) Soil gas contaminant concentrations are monitored during the test, and a reduction of 80 percent or more indicates that SVE is potentially viable for the site and should be further evaluated with additional column studies. If reductions greater than 95 percent are achieved, the residual soil from the column may be analyzed to quantify the residual contamination. If concentrations are below cleanup goals, column tests for remedy selection may be skipped and air permeability tests conducted next.

*c. Remedy selection.* Remedy selection, the next phase of evaluation after technology screening, can include column studies which take weeks to run or air permeability tests, each of which take hours to days in the field. Pilot studies which take weeks or months to run are sometimes required in the remedy selection phase but more typically belong within the remedial design phase of work. Remedy selection column tests are supplemented with additional efforts, including field air permeability tests and mathematical modeling to provide information relative to SVE performance, cost, and design. A strategy recommended by USEPA (1991c) is to:

- Perform column tests to determine whether SVE can meet cleanup goals and if so, over what air flow/time frame.
- If column tests show SVE can meet goals, conduct field air permeability tests to check implementability of SVE.
- Supplement the above with mathematical modeling.
- Conduct pilot-scale testing for remedy selection.

*d. Column tests.* Column tests are not required for most SVE/BV applications, but may be useful under certain circumstances, e.g., venting and/or biodegradation of recalcitrant (difficult to degrade) contaminants. Column tests typically use 2 to 8 kg of contaminated soil (e.g., with column dimensions ranging from 5 to 10 cm in diameter and 30 to 60 cm in length) and are run until results become asymptotic, with duration and cost depending on soil characteristics and the contaminants. Measurements taken prior to the column tests may include bulk density, moisture content, and analyses of contaminant concentrations in the soil matrix, in Toxicity Characteristic Leaching Procedure (TCLP) leachate, and in the headspace. Different airflow rates can be tested to check sensitivity of contaminant removal rates to airflow. Measurements taken during testing include inflow and outflow air pressures, effluent contaminant concentrations, airflow rates, and temperature. After the test, contaminant concentrations in the soil matrix and in TCLP leachate are measured for comparison with cleanup goals. A sketch of a column test apparatus is shown in Figure 4-1. Table 4-1 presents the advantages and disadvantages of column tests.

(1) While column tests are not generally to be relied upon as the sole source of air permeability data, they can provide a useful means to supplement in situ air permeability tests. For example, while in situ  $k_a$  tests can usually be performed in only a limited number of locations, intact cores can often be collected from many locations and depths, including within the in situ  $k_a$  test locations, so that the correlation between laboratory and in situ data can be examined. If the results are well correlated, the laboratory data can be used to generalize the in situ results throughout the sampling area.

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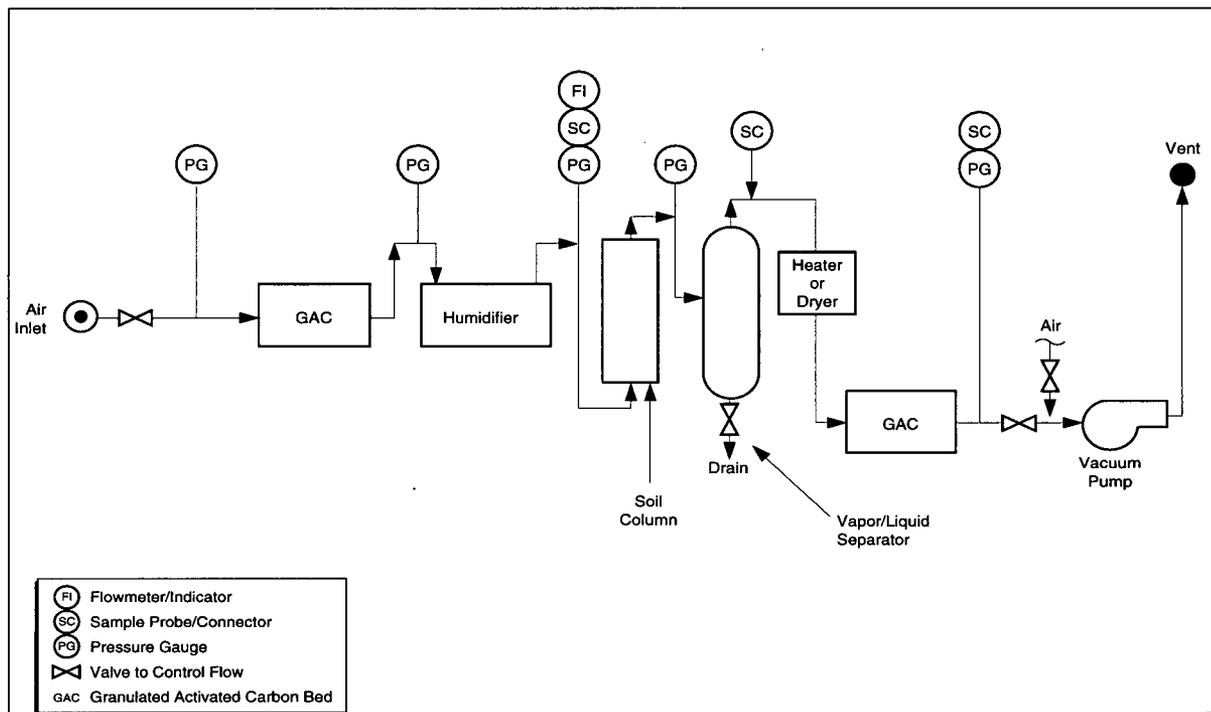


Figure 4-1 Diagram of typical column test apparatus (source USEPA 1991c)

(2) Column tests are best performed using intact core samples. Intact core samples can be obtained using drive samplers or continuous coring devices. Core samples should be collected inside rigid sleeves, and annotated with the sample designation and orientation. The samples should be sealed and refrigerated upon collection to prevent volatilization and degradation of contaminants. Typical drilling procedures recover soil cores in a vertical or near vertical orientation. The typical flow of air during SVE or BV, though certainly three-dimensional, is not vertical and the horizontal air permeability is probably more of interest. This fact should be weighed carefully in deciding if vertical cores are to be collected for testing.

Table 4-1  
Column Test Advantages and Limitations

| Advantages  | Limitations   |
|---|---|
| 1. May accelerate the SVE process to permit evaluation of maximum contaminant removal potential.        | 1. Stripping air always has good access to the contaminants throughout the column. Airflow to different zones varies widely in the field.                                       |
| 2. Gives order-of-magnitude information on the partition coefficients needed for mathematical modeling. | 2. Diffusion processes are often not properly modeled.  |
| 3. Order-of-magnitude air permeability measurements may be obtained with "undisturbed" samples.         | 3. Due to the differences in scale and airflow vs. core orientation, more representative air permeability results must be obtained through field air permeability measurements. |
| 4. Can permit analysis of closely spaced samples.   | 4. Standard procedures must be formulated and validated.  |

After: USEPA 1991c

(3) At the laboratory, core samples can be extruded into test columns, or the sample sleeves can be incorporated into the column setup. If disturbed samples were obtained, the samples should be repacked to a final density approximating field conditions. If the test is designed to simulate vertical flow through a

layered profile, layers can be incorporated during placement of the soil. One should consider collecting intact, horizontally oriented cores if the test is intended to simulate horizontal airflow.

(4) Test equipment typically includes a vacuum or air supply system, flow metering devices, and pressure measurement equipment. Soil moisture measurement devices (e.g., tensiometers) may also be provided. All connections between the air supply system, the column walls, and the soil sample should be airtight. Some columns incorporate an inflatable bladder in the annulus between the core sample and the column wall to prevent leakage along the sides of the soil sample.

(5) Contaminant concentrations can be measured in the solid or vapor phase. Since soil measurements require destructive sampling, measurement points are limited to the initial and final concentrations. Vapor sampling permits time-series measurement of effluent concentrations, but typically requires sophisticated onsite measurement equipment (e.g., gas chromatographs). Vapor measurements should be supported by initial and final soil concentrations. Column tests for BV applications are described in paragraph 4-2g.

(6) Test results are usually expressed as contaminant concentration versus the total volume of air exchanged. To relate column tests to field applications, air exchange is typically expressed in units of pore volumes.

(7) Calculation of pore volumes requires measurement of the sample porosity and dimensions, as well as the flow rate and elapsed time. Results can be used to evaluate the rate of contaminant removal, and estimated residual concentrations. Partitioning coefficients can also be determined, provided equilibrium concentrations are measured concurrently in each phase, along with  $f_{oc}$  (see paragraph 2-3b).

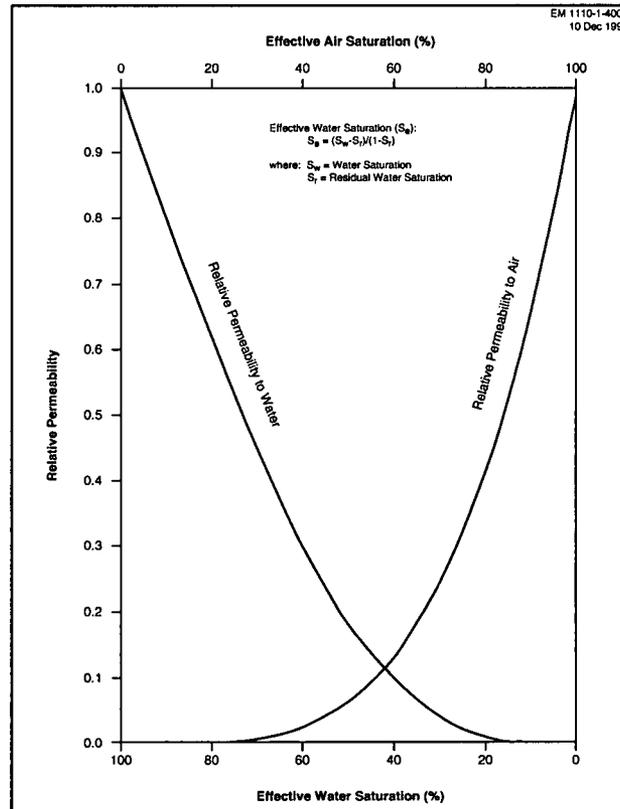


Figure 4-2 Relationship between water saturation and relative permeability to air

*e. Field air permeability tests.* Air permeability tests provide information on the air permeability of different geologic units at the site. Air permeability test data can be used during the initial design to estimate the spacing of vents, anticipated airflow rates, moisture removal rates, and initial contaminant removal rates. Some air permeability tests can be used to determine the anisotropy of the vadose zone (the ratio of horizontal to vertical permeabilities), which is important if the site lacks a surface seal, or if airflow is desired across soil layers.

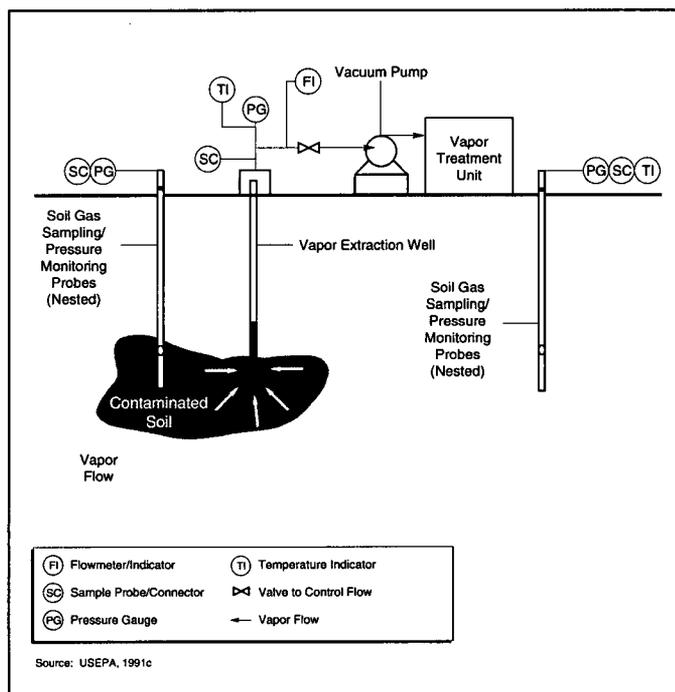
(1) Whereas pilot tests provide information regarding the probable performance of SVE/BV systems, air permeability tests are designed for the specific purpose of determining the permeability of air-filled pore space, and can be used to estimate air-filled porosity (Appendix D). The total pore space in granular

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unsaturated soils is not infrequently occupied by 10 to 30 percent, or more, water. The water content causes a reduction of the pore space available for airflow, resulting in relative air permeabilities, which are less than the soil's intrinsic permeability (paragraph 2-3c). This is of practical significance because although values of relative permeability range only from 0 to 1, values of air permeability typically range over many orders of magnitude, as a function of saturation. Figure 4-2 shows an example of a relationship between relative permeability and air and water content based on the Brooks and Corey (1964) model. Because of the spatial variability of soil properties that is seen at most sites, the  $k_r(S)$  curve and the  $k$  value itself tend to vary considerably among different soils, and even vary within a single location depending on the direction of airflow and the scale of the measurement. Therefore, the reader should not assume that a curve obtained for one location, direction, or scale will necessarily represent another location, direction, or scale.

(2) Air permeability is typically evaluated using analytical solutions for radial flow to a well (Appendix D). The solution used must simulate the boundary conditions encountered during the test. For example, the one-dimensional radial flow solution should be used for geologic units with upper and lower impermeable boundaries (e.g., a surface seal and the water table). If a transient solution is used, pressure measurements should be recorded on a logarithmic time scale. Steady-state solutions can be used for sites that show rapid equilibration of measured vacuums (or pressures).

(3) The one-dimensional radial flow solution (equation 2-20) should be used for sites with an impermeable surface seal, where the test objective is to evaluate the air permeability of the entire vadose zone. One vapor recovery well should be located in the area likely to be remediated. The well should be



**Figure 4-3 Schematic for typical air permeability or pilot test**

the top of the contamination or to no less than 1.5 meters below the surface. Refer to procedures outlined in Shan, Falta, and Javandel (1992) and Falta (1996) for analysis of transient air permeability test data from sites with an air-permeable surface. The analysis procedures of Falta (1996) address both steady state and

be screened from near the water table to near the ground surface. Vacuum (or pressure) measurements can be recorded at existing monitoring wells, or additional soil probes can be installed at various distances and directions from the extraction well, and at varying depths (Figure 4-3). Ideally, measurement points would be aligned in two perpendicular directions, with the spacing between points increasing logarithmically with distance from the well (e.g., 0.2 m, 2 m, 20 m, etc.). The perpendicular orientation allows evaluation of anisotropy within the horizontal plane, and the logarithmic spacing allows preparation of distance-drawdown plots for evaluation of well efficiency and rapid determination of the radius of pressure/vacuum influence (ROI).

(4) It should be noted that open sites and "leaky" sites can also be addressed with analytical solutions. The vapor recovery well in these cases should be screened from the base of the contamination to either near

transient data for covered, leaky, and open sites and are incorporated in the GASSOLVE software available from the USACE HTRW CX (DoD staff and contractors only) or Dr. Falta at Clemson University.

(5) Step Testing and Air Permeability Testing. A "step test" is often done in conjunction with the permeability testing. The step test provides necessary information for design in identifying the relationship between applied vacuum (or pressure) and the resulting flow from an extraction well. These data are needed to select blowers and estimate vacuums needed to achieve a subsurface flow. The step test can be performed by starting the system at the minimum flow rate and increasing the flow stepwise, taking vacuum (or pressure) measurements at the measurement points during each step. The necessary vacuum and airflow rate for the air permeability test is normally chosen following the step test. In some cases, air permeability is determined for more than one step during the step testing.

(6) The key control variables for air permeability testing are airflow rate and the applied vacuum at the extraction well. Transient air permeability tests typically require from one to four hours from start-up to completion. If multiple flow steps are used, one to two days may be required. The results of the air permeability test are then plotted in accordance with the particular solution method used (e.g., Figure 4-4). Steady-state conditions, where vacuums are not changing significantly over a period of an hour or more, may require several hours to days to develop at a constant flow rate. If the test is allowed to continue until steady-state is reached, use the steady-state solutions presented in Appendix D to determine the air permeability or the GASSOLVE software (Falta, 1996). These values provide a good check on the values determined by transient methods. In any case, the analysis of the permeability test data should not use the vacuums observed in the extraction well. This vacuum is affected by the vent efficiency (see paragraph 4-5f(6)).

(7) Table 4-2 presents the advantages and limitations of field air permeability tests. The general procedures for assessing an air permeability test are presented in Appendix D.

*f. Pilot tests.* Pilot tests are conducted to evaluate contaminant removal rates and the distribution of airflow within the contaminated zone. A vacuum is applied at the extraction well, and resulting airflow rates, soil gas vacuum (or pressure) levels, soil and air temperatures, soil moisture levels, and effluent

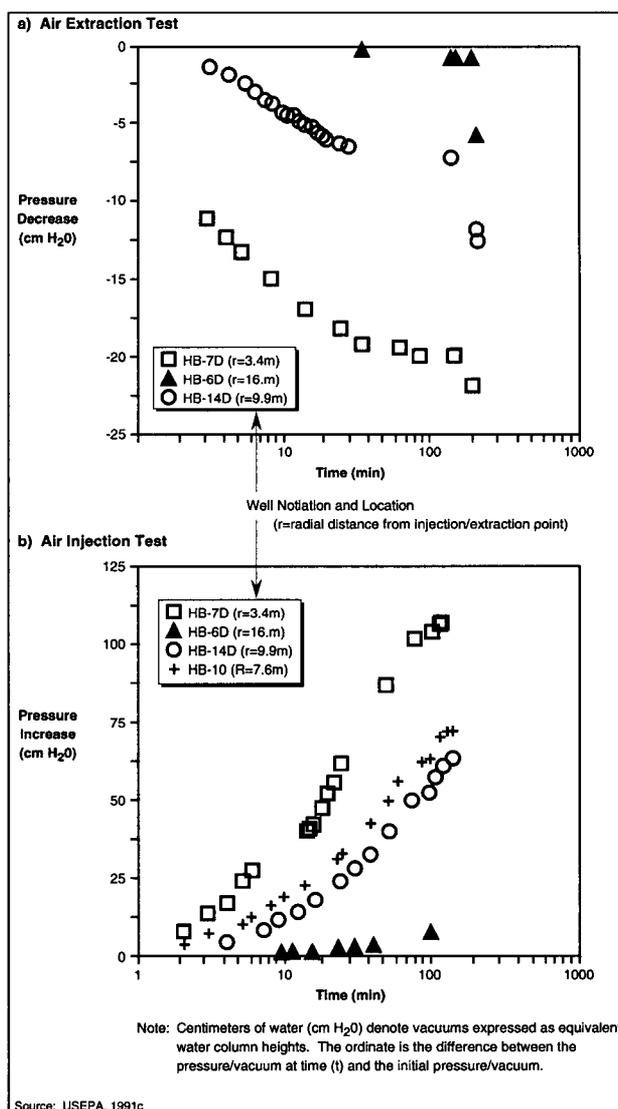


Figure 4-4 Typical field air permeability test data

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contaminant concentrations are measured. Given that many sites are heterogeneous, it is particularly important to measure the spatial distribution of airflow within the zone of influence of the extraction well. The quantity and composition of liquids collected in the air/water separator should also be measured. Overall, the user is advised to refrain from collecting unnecessary data and focus instead on clear identification of test objectives and collection of data that meet those objectives.

(1) Pilot tests may range from several days to weeks in duration, or longer in some instances. Most SVE systems typically show an initial "spike" in effluent concentration, which rapidly declines to a subsequent baseline concentration. The initial spike is commonly representative of initial soil gas concentrations, resulting from equilibrium partitioning into a relatively static air phase. The subsequent baseline concentration represents equilibrium partitioning into a dynamic air phase, which is thought to be limited by diffusion from relatively stagnant areas into zones of more mobile airflow. The difference between the initial spike and the subsequent baseline concentrations depends upon numerous factors, including the rate of airflow, the volatility of the contaminants, biodegradation rates, the proportion of stagnant to mobile soil gas zones, and the degree of interconnectedness between those zones. Since the latter considerations are almost impossible to predict, pilot tests are commonly performed to evaluate sustainable baseline concentrations.

**Table 4-2**  
**Field Air Permeability Test Advantages and Limitations**

| Advantages   | Limitations   |
|--|---|
| 1. Provides the most accurate air permeability measurements.   | 1. May give low air permeability measurements in soil zones where significant water removal may later take place during the operation of the SVE/BV system. |
| 2. Permits measurements of the air permeability of several geological strata                             | 2. Only provides an approximate average permeability for the strata and provides only indirect information about the site heterogenities.                   |
| 3. Measures the radius of influence in the vicinity of the test point.                                   | 3. Requires a health and safety plan and may require special protective equipment.  |
| 4. When coupled with analytical measurements, gives information about initial contaminant removal rates. | 4. May require an air permit on non-NPL sites.  |
| 5. Provides information for designing a pilot-scale test.  | 5. Cannot be used to measure air permeability in a saturated zone that will be dewatered prior to application of the technology.                            |

Source (in part): USEPA 1991c

(2) The offgas concentration versus time history can, at times, clarify the location of the contamination relative to the test well: an increasing level of contaminant over time can indicate contaminant at distance from the extraction point; whereas a decreasing level over time tends to be indicative of normal transport of contaminant located within the zone penetrated by the well.

(3) The aboveground portion of the pilot system -- consisting of a blower or vacuum pump, ambient air intake, airflow meters, pressure gauges, vacuum gauges, temperature indicators, air-water separator, offgas treatment equipment, and power supply -- is often mounted on a mobile unit. The below-ground portion of the system consists of at least one extraction and/or injection well and at least three probes or monitoring wells to measure soil pressure at various depths and distances from the extraction point. These should be equipped with sampling ports.

(4) Offgas treatment, if required, is usually by adsorption to granular activated carbon; however, incineration, catalytic oxidation, or condensation may also be used. Pilot testing for SVE can also represent an opportunity to pilot test offgas-treatment methods for technology selection and cost estimating purposes. Refer to other guidance for further information regarding offgas treatment. Sampling ports for offgas treatment influent and effluent should be provided. Water treatment is usually accomplished using granular activated carbon or biological treatment. Field tests typically cover areas ranging from several square meters to several hundred square meters. If the site is likely to be covered during full-scale implementation (see paragraph 5-16), an impermeable layer, e.g. polyethylene, is often placed on the ground surface prior to the pilot test to prevent short-circuiting of aboveground air. The extraction flow is established, and pressure profiles and airflow rates are measured as a function of time until they stabilize. Then contaminant concentrations before and after the treatment system and in the ambient air are analyzed. Moisture levels in the effluent gas and the water level in the air-water separator are monitored. The pilot-scale system can later be incorporated into a full-scale SVE/BV system if desired. Additional information on conducting pilot tests is found in paragraphs 4-5 and 4-7.

(5) By profiling the concentrations and flow rates extracted from discrete depths or soil strata, e.g., using the PneuLog® tool (see paragraph 4-6g), it is possible to further refine the site conceptual model and understand the effects of soil venting on the subsurface. By determining the extent to which contamination is removed from different strata, it is possible to determine the optimal locations for well screens. Vertical profiling of extracted concentrations and flow rates can also aid in understanding the extent to which diffusion limited mass transport will occur. For example, consider a site where vertical profiling data indicate that the majority of the contamination is extracted from between 18 and 20 feet bgs (below ground surface), but that strata produces an order of magnitude less air flow than the 5 feet above and below. An SVE well screened at this depth will primarily extract air from the more permeable layers above and below the contaminated zone. Advective transport through the low permeability soil will be minimal. Cleanup of this soil will occur primarily through diffusive flux from the low permeability soil into the adjacent higher permeability layers.

(6) Collection of confirmatory soil samples is not advocated during or after performance of pilot tests of limited duration (e.g., weeks). A large number of samples would need to be collected to encompass spatial variability of contaminant distribution, in view of the fact that soil sampling is a destructive technique and no point can be sampled twice. The relatively small concentration changes to be expected therefore do not generally warrant the effort that would be required to discern significant trends.

*g. BV Microcosm, column, and field tests.* Microcosm tests can be useful in BV applications. Kampbell and Wilson (1991) describe microcosms for evaluating biodegradation of vapor phase contaminants using 160-ml serum bottles. Nutrient concentrations, moisture levels, and temperatures can be varied to optimize conditions for biodegradation, and biodegradation kinetics can be determined by gas chromatography analysis of vapor samples over time (Ostendorf and Kampbell 1990). Richards, Ostendorf, and Switzenbaum (1992) describe a microcosm design utilizing a Mininert™ valve for vapor sample collection and a water seal to overcome the problem of vapor leakage from microcosms over time. Vapors were held in abiotic controls for as long as six months. Abiotic controls were effectively sterilized by autoclaving soil microcosms at 394 °K for one hour on each of three consecutive days.

(1) Baker et al. (1994a,b) describe a column study method using radiolabeled compounds. Such testing is useful for evaluating the feasibility of BV when there is a concern that the target compounds may not be completely mineralized. Contaminated soil is packed into columns and <sup>14</sup>C-labeled target compounds are added as a tracer. The column is subjected to an advective airflow, and vapor phase contaminants and carbon dioxide are trapped on adsorbents such as Tenax™ and sodium hydroxide,

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respectively. Any leachate generated is also analyzed for  $^{14}\text{C}$ . At the end of the experiment, extracting the soil with organic solvents completes the mass balance and chromic acid is used to oxidize the extract and measure the mass remaining as parent compounds, metabolic intermediates, and carbon incorporated into biomass.

(2) Intact soil cores are not typically used in bench-scale tests in practice. However, methodology has been developed using columns containing intact soils for research of soil venting (Ostendorf et al. 1993a), air sparging (Ostendorf, Moyer, and Hinlein 1993b), and BV (Moyer 1993). These columns are equipped with vapor sampling ports at 30-mm intervals so that vertical concentration profiles can be analyzed by gas chromatography of vapor samples.

(3) In many situations involving waste materials (e.g., fuels) that are known to be biodegradable, and for which BV systems have been applied successfully at numerous sites, field-scale testing is more appropriate than performance of microcosm or column studies. The key to assessment of the viability of BV for a given site then is to describe soil/site limitations that may compromise the success of a BV system. These site/soil limitations can be assessed effectively through field-scale tests.

(4) The U.S. Air Force has developed a protocol for field treatability testing of BV (Hinchee et al. 1992; Leeson and Hinchee, 1995). Biodegradation ("respiration") rates are estimated by measuring the change in oxygen and carbon dioxide concentrations in the soil gas of contaminated and uncontaminated soil after it has been vented with air. A venting well is installed in an area of contaminated soil, and a background well is installed in a similar but uncontaminated area. The purpose of the background well is to provide an estimate of natural background respiration of soil organic matter. A minimum of three soil gas monitoring point clusters are installed at varying distances from the venting well in the contaminated soil. Each monitoring point cluster is screened at two or three depths. Air with 1 to 2 percent helium is injected for at least 20 hours at a rate of 0.03 to 0.05 cubic meters per minute (1 to 1.7 cubic feet per minute) into the venting and background wells. This is typically sufficient for creating large enough air-suffused zones and oxidizing any ferrous iron which may be present in the soil. Measure oxygen content of soil gas samples from the monitoring points to confirm adequate aeration of the subsurface. Air injection is then discontinued, and oxygen, carbon dioxide, and helium concentrations are monitored over time in the wells and monitoring points using portable meters, at 2-hour intervals at first, and later at 4- and 12-hour intervals. The injected helium acts as a conservative tracer that enables assessment of the extent of dilution of the injected gases through processes such as gaseous diffusion from the aerated zone. The in-situ respirometry test is terminated after a predetermined time period, usually between 3 and 5 days, or when the oxygen concentration is reduced to 5 percent (Leeson and Hinchee, 1995). The time period is based on the practitioners understanding of the site, and the practical considerations of staffing the test. Note that although the Air Force protocol recommends air injection into the monitoring points, the injection of air via only the vent well is more representative of the full-scale implementation of bioventing and provides information on the difficulty in delivering adequate oxygen to the site soils.

(5) The air injection test provides an opportunity to measure both respiration rates and air permeability determinations. By measuring the pressure/vacuum changes over time at several monitoring points in the soil away from the venting well during the injection (or extraction) of air at a constant rate from a single venting well, the data can be collected for calculating air permeability. Although air injection is the preferred recommended method for aerating the soil for BV testing, vapor extraction is an acceptable alternative. Air can be extracted from the vent, drawing in oxygen-rich air into the test volume. Air permeability under air injection may differ from permeability under extraction conditions. The applied pressure forces soil moisture away from the well and may significantly depress the water table and

capillary fringe. BV testing by vapor extraction prohibits the use of a conservative tracer (e.g., helium) for assessment of the effects of dilution/diffusion.

(6) Oxygen uptake rates, corrected for background respiration and diffusion (i.e., based on recovery of a tracer gas), are converted to contaminant degradation rates by assuming a stoichiometry. To calculate a bulk hydrocarbon biodegradation rate, Hinchee et al. (1992) assume that the observed oxygen uptake rate is attributable to mineralization of an equivalent hydrocarbon, which in the case of a petroleum mixture such as jet fuel (JP-4 or JP-8) is hexane. An appropriate stoichiometry should be selected for any specific contamination problem. This simple, rapid, inexpensive field test is useful for estimating the biodegradation rate of bulk hydrocarbons but does not provide information on biodegradation rates for individual compounds of special interest, such as benzene, when multiple contaminants are present. Carbon dioxide generation rates are not typically used because non-biological carbon dioxide sinks in the subsurface -- such as reaction with carbonates to form bicarbonates, especially in alkaline soils -- can cause biodegradation rates to be underestimated (Hinchee and Ong 1992). Baker (1999) points out that at some sites, similar non-biological reactions of oxygen can cause biodegradation rates to be overestimated. Reduced inorganic species, such as  $Fe^{+2}$ , in an area that has been anoxic for an extended period can exhibit a significant chemical oxygen demand that is indistinguishable from biological oxygen uptake. As described in paragraph 3-4f, Cho et al. (1997) attributed some of the overestimate of biodegradation at the USCG Support Center, Elizabeth City, NJ to inorganic chemical oxygen demand. Despite these potentially confounding factors, in situ respiration based on oxygen uptake measurements can be used to guide the decision making process in the selection of the timing of the collection of more expensive confirmatory soil core samples that must be done to positively verify remediation system performance.

#### **4-3. Bench- and Pilot-Scale Testing Strategy**

The general approach described above is illustrated in Figure 4-5.

*a.* The testing sequence and schedule will depend on a variety of site-specific factors. For example, in the case of a sudden release of VOCs next to a water supply, the best course of action, given positive results of a quick screening evaluation, may be to install a SVE system and start up quickly, at least attempting to mitigate the hazard while studying longer term options. At the other extreme, the optimal approach at a complex site with a potentially long-term release of contamination may involve more extensive evaluation prior to full-scale implementation.

*b.* The level of testing will also depend on the evaluator's uncertainty as to whether the technology will meet goals cost-effectively. In the case of a perchloroethylene (PCE) spill residing in uniform sand high in the unsaturated zone with reasonable cleanup goals, for example, little if any bench-scale testing would be needed prior to pilot-scale testing. In many instances the pilot-scale testing equipment can be used as part of the final remediation. The level of effort in testing will reflect the combined judgment of the customer, designer, and regulators.

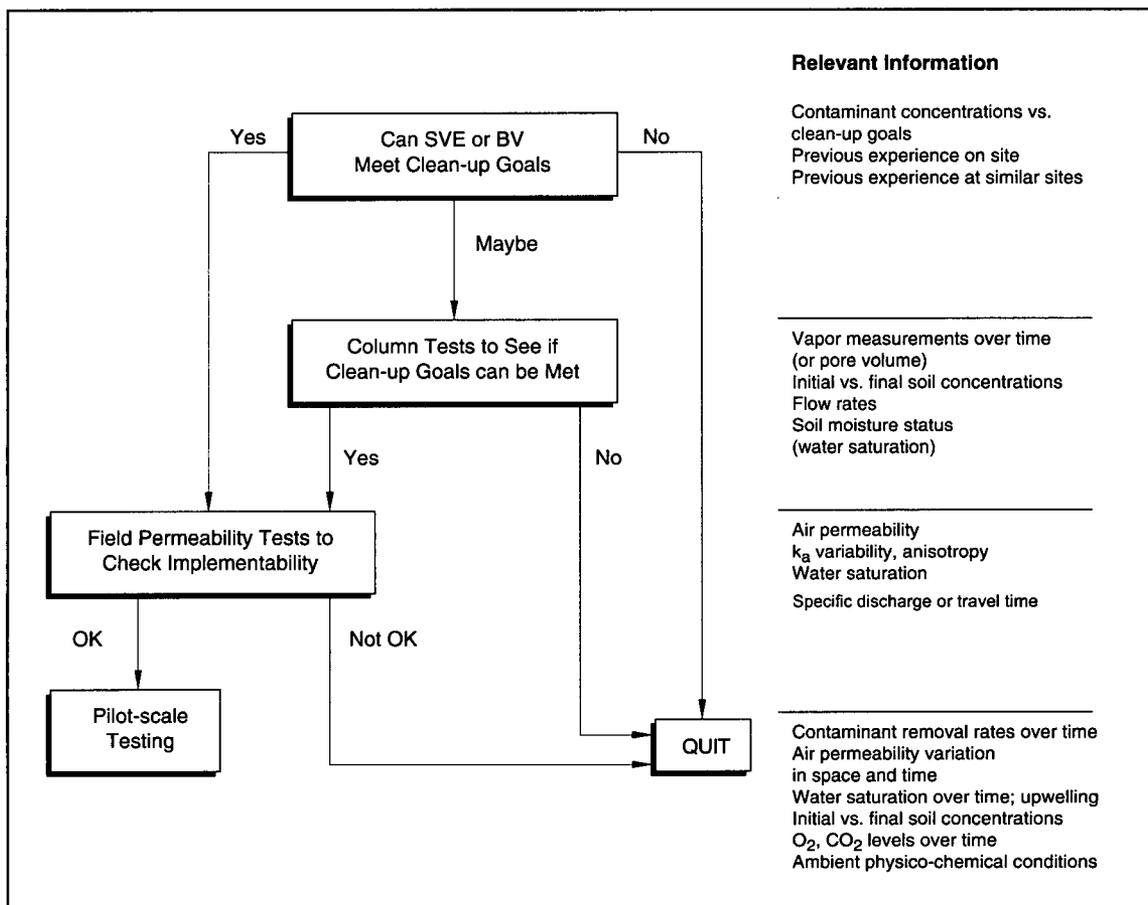


Figure 4-5 Bench- and pilot-scale decision tree

4-4. Work Plan

a. A formal work plan should be prepared as the first step in the planning of an SVE/BV screening test. Usually, a work plan will be required by the regulatory overseer. The work plan should identify and address not only the scope of work to be performed during the test, but also the data objectives, health and safety procedures, and scheduling issues associated with the test. A checklist for review of plans for SVE and BV pilot tests is provided as Table 4-3.

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**Table 4-3**  
**SVE Pilot Test Workplan Review Checklist**

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Project objectives described? Can include:

- Determine air permeability
- Determine radius of influence
- Determine flow rate vs vacuum (for blower sizing)
- Determine initial soil gas concentrations
- Determine "long term" soil gas concentration trends
- Determine condensate production
- Determine water table response

Site History and use described?

Site conditions summarized? Should include:

- Site stratigraphy
- Water table elevation and fluctuations
- Site surface conditions
- Site utilities (overhead and buried)
- Site contaminants and Contaminant distribution
- Possible offsite sources

Project personnel and responsibilities identified?

Well locations specified on layout plan?

Wells at least 4" diameter? (smaller wells ok for soil gas and vacuum monitoring)

Well diagrams required?

Boring logs required?

Drilling method identified? No fluids used in drilling?

Continuous wrap screen used?

Appropriate materials used for contaminants expected?

Soil samples taken as required?

Soil sampling techniques described?

Soil samples analyzed for appropriate contaminants?

Soil samples analyzed for geotechnical parameters: gradations, moisture?

Soil samples analyzed for total organic carbon?

Well screen placed properly (not too shallow, not too long, etc.)?

Filter pack used, sized for screen slot?

Seal placed above the filter pack?

Remainder of annulus grouted with cement grout (preferred)?

Well head completion appropriate for current site use?

Vacuum/pressure/vapor monitoring point construction specified?

Vacuum/pressure/vapor monitoring point locations shown on layout?

Equipment schematic provided?

Blower provided that has adequate flow/vacuum range for soil type?

Blower specs should be given

Power source for blower stated?

Air/water separator provided?

Particulate filter provided upstream of the blower?

Vacuum/pressure relief valves provided upstream, downstream, respectively, of blower?

Temperature gauges provided upstream and downstream of blower?

(Sheet 1 of 2)

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**Table 4-3**  
**(continued)**

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- Sample ports provided at each well?
- Sample ports provided ahead of blower and after treatment unit?
- Air bleed-in valve upstream of blower?
- Flow control provided at each well head?
- Flow measurement device provided (and ports to measure total flow and individual well flows)?
- Piping layout provided and practical, economical?
- Piping materials appropriate size and material for contaminant?
- Piping protected from damage (physical, sunlight)?
- Piping placement or support addressed?
- Condensate drainage considered in piping design?
- Heat tracing or piping insulation appropriate?
- Offgas treatment provided if necessary (both regulatory and safety reasons)?
- Test Procedures:
  - System startup (check for blockages, piping leaks, blower rotation, etc.)
  - Test operational sequence (wells used, flow rates, etc) described?
  - Vapor sample schedule described?
  - Vapor sampling procedures, equipment, and locations (include offgas) described?
- Vapor analysis techniques & analytes:
  - equipment
  - analytical methods (PID, on/offsite GC analysis, explosimeter)
  - appropriate contaminants (CO<sub>2</sub>, O<sub>2</sub>, CH<sub>4</sub> included if looking at biological activity (pre-test and early test samples preferred)
- Vacuum, flow, and other physical measurement frequency and location specified?
- Instruments for vacuum, flow measurement specified?
- Maintenance personnel and procedures (if pilot extends over a long term)?
- Monitor ground water levels/response?
- Monitor barometric pressure?
- Monitor precipitation?
- Data analysis:
  - Air permeability analysis appropriate for boundary conditions?
  - System curve construction?
  - Zone of Adequate Air Exchange identified appropriately?
  - Biological activity (rate of degradation) determined?
  - Mass removal calculations?
  - Extrapolation of concentration trends (total, specific contaminants) performed (if appropriate)?
  - Modeling considered as part of the analysis?
- Report outline provided?
- Condensate disposal addressed?
- Investigation Derived Waste (IDW) disposal addressed?
- Well abandonment (if appropriate) described?]

At a minimum, the elements of a typical work plan are listed below:

*b. Project description.* This section should include a description of the site, the geologic and contaminant conditions, and a brief site history that describes land use, identifies the types of chemicals used or produced, and summarizes the status of the remediation or investigation.

*c. Remedial technology description.* This section should provide a description of the SVE/BV process and any ancillary technologies to be used in conjunction with SVE/BV. In addition, any site specifics that would impact either the screening test or a full-scale design should be described here, such as a hydrogeologic interpretation of the test site and general area (i.e., a conceptual model of the salient conditions that will impinge upon in situ treatment).

*d. Test objectives.* This section should outline the goals of the screening test. The objectives of the test should address relevant decisions to be made, the required quality of the data, and the data that the test will provide to make those decisions.

*e. Experimental design and procedures.* This section should provide information on the critical parameters to be studied and evaluated during the screening test, as identified in the test objectives. Depending on the level of screening or the scale of the test (bench versus pilot), this section should include: 1) descriptions of equipment, 2) site layout, 3) site selection rationale (ideally the test site will be representative of the area to be remediated by the full-scale SVE/BV system), 4) extraction well and monitoring point installation and construction (see Chapter 5), 5) test procedures, 6) test sequence and duration, 7) anticipated flow rates and contaminants, 8) schematics, 9) sampling and analysis procedures, and 10) Quality Assurance/Quality Control (QA/QC) requirements including DQO.

*f. Management and staffing.* This section should identify the management and technical personnel involved in carrying out the test, including all subcontractors and regulatory coordinators.

*g. Equipment and materials.* Depending on the level of detail provided in the experimental design and procedures section (above), this section may be included as an appendix to the work plan. In any case, this section should include a specification list for all major equipment and materials to be used in carrying out the screening test, along with well and vent construction details (proposed or pre-existing).

*h. Sampling and analysis.* A sampling and analysis plan (SAP) is needed for any bench- or pilot-scale study. This plan, which is usually prepared after the work plan, may be specific to the actual screening test, or it may be derived from an approved plan for the entire project or a particular phase (such as the Remedial Investigation/Feasibility Study (RI/FS) or Remedial Design) in the remedial process. As with equipment and materials, this section may be adequately discussed in the experimental design and procedure section. In such a case, the SAP may be included as an appendix to the work plan. The SAP should include the procedures for data quality validation, including calibration checks, duplicate sample analysis, matrix spikes, etc. Provisions should be set forth to assess the precision, accuracy, and completeness of all data in relation to the DQOs that were specified in the experimental design and procedures section.

*i. Data management.* This section should discuss the format in which the various data will be collected and presented in the study report. It should also describe any tools (i.e., computer software, data

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loggers, chart recorders, spreadsheets, numerical methods, and other references) that will be used to translate raw data into a clear, concise, and presentable format.

*j. Data analysis and interpretation.* This section should describe the data reduction procedures to be used. Depending on the scale of the screening test, the data might include analytical results, physical parameters (i.e., pressure, temperature, and flow rates), and soil properties (porosity, bulk density, moisture content, etc.). This section should propose the methods of the air permeability analysis, system curve construction, biodegradation rate analysis, mass removal calculation, and concentration extrapolation analysis, among others. This section should also provide examples of the graphs, charts, and tables to be presented in the study report.

(1) This section, or a separate Quality Assurance Project Plan (QAPP), should also describe the QA/QC procedures that ensure the reduced data accurately represent the original data.

(2) Finally, this section should address the methods by which the collected data will be compared to the test objectives that were presented previously in the work plan.

*k. Health and safety.* This section should outline the site-specific health and safety procedures to be followed by all workers involved in performing the screening test. Typically, this section is derived from a Site-specific Safety and Health Plan (SSHP) developed previously in the remedial process. If a SSHP has not been developed, then detailed procedures addressing all relevant aspects of occupational health and safety must be provided in accordance with the requirements of ER 385-1-92 and EM 385-1-1 (see paragraph 11-3 herein).

*l. Residuals management and regulatory compliance.* This section should describe the procedures for managing all Investigation Derived Waste (IDW), including contaminated soil and groundwater, spent granular activated carbon, used personal protective equipment (PPE), sample handlers and containers, and any other materials that are or may become potentially contaminated as a result of the screening test. This section should include permit and approval requirements, if any, pertaining to offgas collection and treatment, as well as other IDW.

*m. Community relations.* This section should describe all actions that will be employed to inform the surrounding community about the screening test and to receive feedback and comments from the public regarding the test. This section is typically covered by a superseding, sitewide Community Relations Plan, although some topics specific to the screening test may need to be addressed directly.

*n. Reports.* This section should present a listing of all interim and final reports to be prepared. It should also introduce the format for the presentation of the final report.

*o. Schedule.* This section should discuss the schedule for completing the various milestones in the screening test process. The schedule should list the start and end dates for each task to be performed. Bar charts are typically used as a convenient format for presenting the schedule. Consideration should be given to the unavoidable constraints placed on tests by weather conditions (e.g., likelihood of snow, ice, and frozen--and thus impervious--soils during winter, and high water table conditions during rainy seasons or snowmelt).

#### 4-5. Test Performance and Data Analysis

This section provides a general description of the

- Objectives.
- Preparation.
- Equipment.
- Methods.

for conducting field pilot-scale SVE/BV performance tests.

*a. Objectives. In general, field pilot-scale SVE/BV performance tests are conducted to evaluate*

- Site-specific vent performance characteristics such as capacities and subsurface vacuum distributions for various vent geometries and configurations.
- In situ air permeability as a function of space and time, especially if separate in situ air permeability testing was not previously performed.
- Concentrations of contaminants, O<sub>2</sub>, CO<sub>2</sub>, and water in recovered vapors.
- Potential effects on the water table and the capillary fringe induced by SVE/BV.

(1) Field pilot-scale performance testing is often a critical step in designing a full-scale SVE/BV system. Ultimately, several phases of performance tests may be required to complete a given SVE/BV system design. Consequently, it is important that the personnel responsible for conducting the tests are aware of the overall project objectives to ensure that the appropriate data are collected. Alternatively, the "pilot test" could be considered the first phase of implementation of the full scale SVE system, such that the "pilot" operation is continued while the subsequent phases are designed.

(2) The costs, scheduling, and DQO of the performance tests should be tailored to reflect the objectives of the overall project. For example, if the objective of pilot-scale performance testing is to determine whether vents could be constructed to effectively aerate the soil at a given site, a fairly simple and inexpensive test could be designed to enable a go, no-go decision to be made. Similarly, if the objective is to support the design of a straightforward BV system for treatment of petroleum hydrocarbons, following existing AFCEE/USEPA bioventing guidance will suffice (Leeson and Hinchee et al. 1995).

(3) In most cases, SVE/BV pilot-scale performance tests provide an opportunity to collect data toward achieving other objectives tangential to SVE/BV performance, such as

- Gathering additional site characterization data.
- Evaluating monitoring, vapor recovery, and vapor handling equipment.

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- Evaluating the potential effectiveness of vacuum-enhanced groundwater and free-product recovery systems.

(4) These ancillary objectives should be incorporated in the SVE/BV pilot performance tests only to the extent that achieving these objectives will benefit the overall project. Paragraph 4-2 provides an overview of pilot-testing objectives.

(5) Finally, given the uncertainties and potential exposure to explosive or toxic vapors while performing pilot SVE/BV tests, it is critical that health and safety and regulatory concerns and objectives are defined prior to conducting the tests. These concerns and objectives must be incorporated to ensure that the proper equipment, personnel, and procedures are in place to conduct the tests. Performance testing can be dangerous and, in some cases, a reduction in the scope of the tests may be warranted to reduce risks to acceptable levels.

(6) The following sections provide descriptions of the preparation steps, equipment, and procedures required to perform "typical" pilot SVE/BV performance tests.

*b. Preparation.* Prior to conducting the test, the work plan, site characterization data, overall project objectives, health and safety plans, and Applicable or Relevant and Appropriate Requirements (ARARs) should be reviewed as applicable (see paragraph 4-4).

*c. Equipment.* Figure 4-6 provides a simplified process flow diagram for conducting a typical SVE/BV performance test. Key components include:

- Power supply.
- Subsurface vents, valves, and monitoring ports.
- Vacuum gauge on vent well.
- Vacuum blower.
- Demister or condensate tank.
- Ambient air intake and dilution valves.
- Air pressure relief inlet.
- Particulate filters.
- Vapor, vacuum, temperature, and flow monitoring ports.
- Flow measuring device (appropriate for SVE, such as pitot tube or hot wire anemometer, refer to paragraph 8-3a)
- Vapor discharge stack.

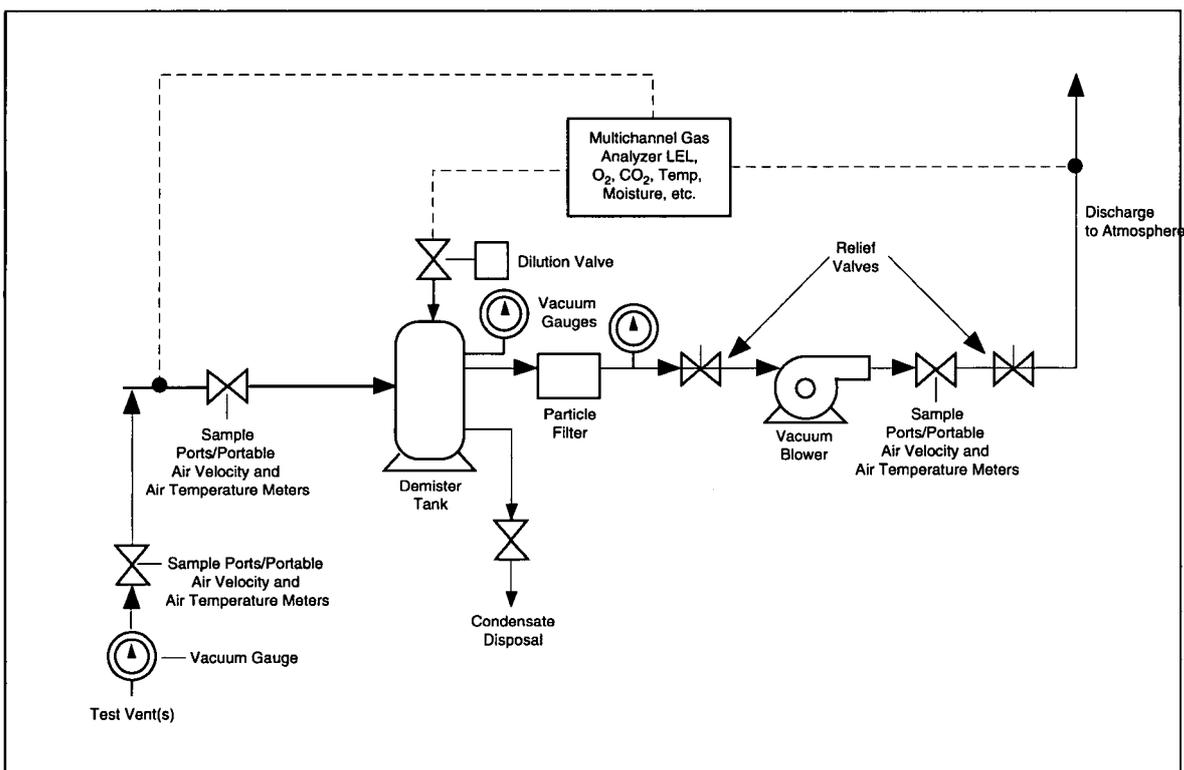


Figure 4-6 SVE/BV system performance test typical procedures

- Multichannel gas analyzer.
- Barometer.

As a general rule, open sites exhibiting 3-D airflow should have a minimum of three monitoring probe clusters placed within a radial distance of <math><2</math> times the depth to water table (DTW) for low permeability settings, and within a radial distance range of 1-3 DTW for high to mixed permeability sites (Peargin and Mohr 1994.) Additional equipment could include vapor treatment units; silencers; variable speed motor drive for the vacuum blower; demister tank high-level alarm and pump; water and/or NAPL recovery wells, oil-water separator and associated controls/monitoring points/treatment units; and soil moisture monitoring devices. More detailed descriptions of well construction, SVE/BV monitoring equipment, process controls, and methods are provided in Chapter 5.

*d. Pilot-testing strategy.* This paragraph discusses approaches typically used to evaluate vent capacities, areas of influence, and efficiencies. The methods are in many ways analogous to common water well testing procedures and are usually conducted in conjunction with permeability tests. A decision tree for pilot testing is shown in Figure 4-7.

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(1) Two basic performance test methods are typically used in SVE/BV pilot tests:

- Stepped-rate tests for estimating vent capacities and system curves.
- Constant-rate tests for evaluating vent areas of influence and efficiencies and air permeabilities.

(2) As in water well testing procedures, a stepped-rate test is usually conducted first to determine the actual capacity of a given vent or vent geometry and to select a flow rate for conducting constant-rate tests. Stepped-rate tests usually take a few hours to complete.

(3) Constant-rate performance tests are usually conducted after the stepped-rate tests to evaluate the actual area of influence and efficiency of a given vent or combination of vents. Constant-rate performance tests are usually conducted under steady-state conditions (i.e., when subsurface vacuums stabilize) to ensure that an empirical and representative (no transient effects) area of influence is obtained. Constant-rate performance tests can take several hours to several days to complete.

(4) Constant-rate performance tests can be conducted following transient air permeability tests (i.e., of shorter duration) (see paragraph 4-2e and Appendix D). The constant-rate/steady-state data provide an additional estimate of air permeability.

(5) Vent efficiencies (head losses between the vent and subsurface soil) can also be estimated from the constant-rate performance test data. The vent efficiency is often a critical factor in interpreting area of influence data and estimating permeability. Without taking into account vent efficiency and using the test vent as an observation point of subsurface vacuum, an anomalously low pressure point is usually observed for the test vent. If such data are then included in the evaluation of permeability and radius of influence, erroneously low values are usually calculated.

*e. Stepped-rate performance tests for vent capacities.* Stepped-rate tests can be conducted on either vertical or horizontal vents and are used to evaluate the vapor recovery rates obtainable at various applied vacuums (vent capacities). The stepped-rate test data are used to develop the “system” curve; the air yield from the well versus the applied well-head vacuum. This information is critical in designing the vents, determining optimum recovery rates, and specifying blowers for the full-scale SVE/BV system.

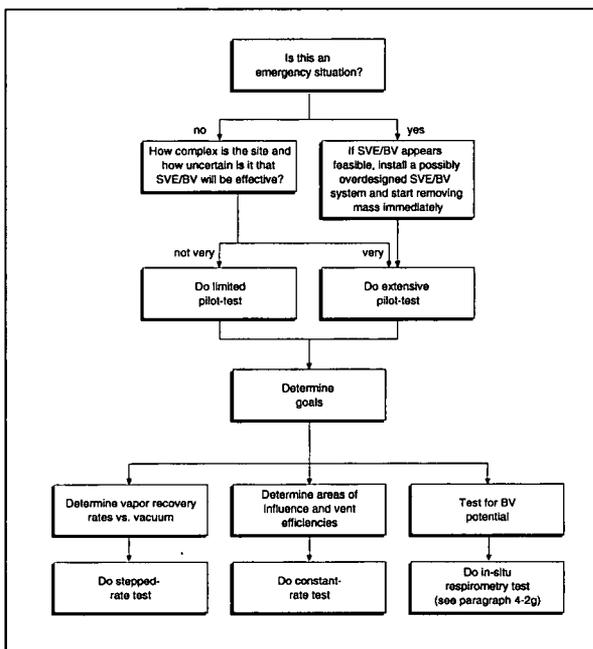


Figure 4-7 Pilot testing decision tree

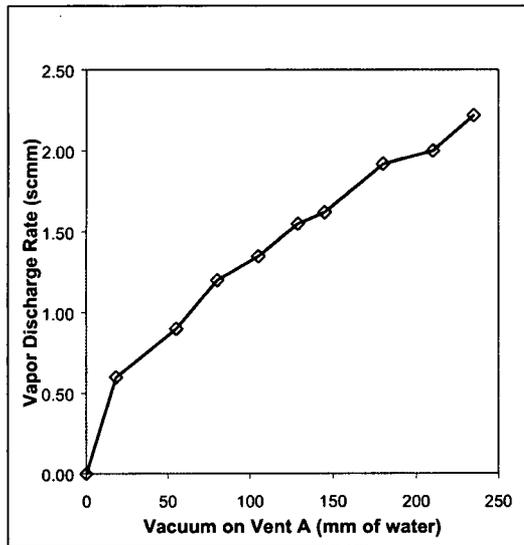


Figure 4-8 Stepped-rate test example for a horizontal vent

(1) In general, a stepped-rate test consists of applying various vacuums on a test vent in a series of equal time steps and measuring the vapor flowrate for each step. A typical test usually takes a few hours per vent to complete. Stepped-rate tests for SVE/BV vents differ from water well tests in that increasing vacuum (drawdown) on the vent does not, in all cases, result in higher recovery rates. This effect results from upwelling of the water table and capillary fringe induced by the vacuum on the vent. In some cases, the saturated zone rises enough to block the well screen and restrict flow to the vent. Consequently, SVE/BV stepped-rate tests are often designed for constant vacuum (drawdown) rather than constant flow rates for each step. The data are plotted on a graph with vapor flow rate on the vertical axis and the applied vacuum on the horizontal axis. The resulting graph is a performance curve for the vent. Figures 4-8 and 4-9 provide example vent performance curves for a horizontal vent and a vertical vent, respectively. Vapor

discharge rate is given in standard cubic meters per minute (SCMM).

(2) The following paragraphs summarize the steps required to size the test blower and conduct a stepped-rate test. For additional information refer to Johnson et al. (1990a).

(3) To size the blower for the stepped-rate test, the steady-state flow equation for radial flow to a vertical vent can be used to estimate the required vacuum to obtain a target flow rate (note that this may not be appropriate for leaky or open sites!):

$$P_{wt} = 1/2 \left\{ \frac{Q_T \mu_a \ln(R_w / R_l)}{Lk_a} + \left[ \left( \frac{Q_T \mu_a \ln(R_w / R_l)}{Lk_a} \right)^2 + 4P_A^2 \right]^{1/2} \right\} \quad (4-1)$$

where

$P_{wt}$  = target absolute pressure at test vent [ $ML^{-1}T^{-2}$ ]

$Q_T$  = target flow rate [ $L^3T^{-1}$ ]

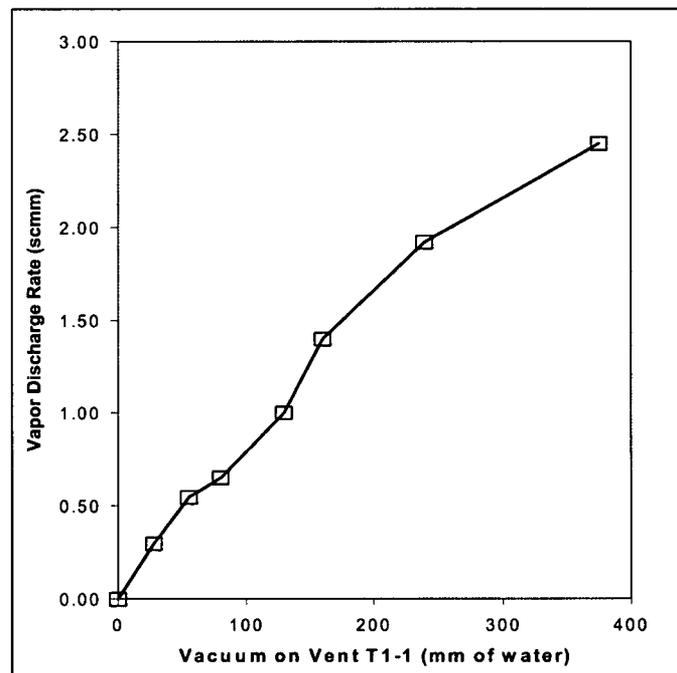


Figure 4-9 Stepped-rate test example for a vertical vent

**EM 1110-1-4001****3 Jun 02** $\mu_a$  = viscosity of air [ $\text{ML}^{-1} \text{T}^{-1}$ ] $R_w$  = radius of test vent [L] $R_l$  = radius of pressure influence for test vent [L] $L$  = effective vent length [L] $k_a$  = estimated air permeability [ $\text{L}^2$ ] $P_A$  = absolute atmospheric pressure [ $\text{ML}^{-1} \text{T}^{-2}$ ]

(4) The target flow rate ( $Q_T$ ) should be high enough to remove the number of soil pore volumes from the contaminated zone required by the final SVE/BV design. The volume of soil that receives the required number of soil volume exchanges in an acceptable timeframe is defined as "the zone of effective air exchange." Chapter 5 offers methods to estimate the necessary flow for various vent geometries. For example, if the target venting rate required to achieve sufficient removal of VOCs from a covered site with one vent were 3 soil pore volumes per day, then the target flow rate could be roughly estimated by

$$Q_T = \frac{3/\text{day} \cdot \pi R_E^2 b n_a}{1440 \text{ min/day}} \quad (4-2)$$

where

 $R_E$  = extent of zone of effective air exchange of test vent (cm) $b$  = unsaturated zone thickness (cm) $n_a$  = effective (air-filled) soil porosity (dimensionless)

(5) The zone of effective air exchange for the vent is generally unknown; however, a range of 5 to 15 meters provides reasonable estimates for many cases. In general, shallow vents have less extensive areas of influence than deeper vents in similar soil and with similar surface and subsurface features. Further discussion of these concepts is found in paragraph 4-5f(20).

(6) Air permeabilities can be roughly estimated based on soil texture; estimated to within approximately an order of magnitude based on moisture retention curves and saturated hydraulic conductivities measured in similar materials; or measured in laboratory or field tests. Likewise, effective (air-filled) soil porosities can be estimated from soil texture and moisture, or determined from laboratory capillary pressure head-saturation tests.

(7) The test blower should be selected using the anticipated vacuum and flow levels. The blower should be selected so as to allow flexibility in accommodating some deviation in the site conditions.

Generally, a blower that can provide reasonable air flow at a wide range of vacuums would be preferred for this purpose. Refer to Chapter 5 for more information on blower selection.

(8) The blower selection must account for piping losses, especially if the test requires the blower to be located a great distance from the extraction well or if multiple extraction wells are to be used. Piping size should be selected to reduce the pressure drop to reasonable levels. As much as 80 to 90 percent of the vacuum can be lost in test equipment piping and through the vent if the piping is inappropriately sized. Consequently, a larger blower would be required to achieve the desired flow rates and vacuums at the vent, which adds cost to the project. Additional information regarding head losses in piping and equipment can be found in Chapter 5.

(9) The use of a variable speed motor drive on the blower is particularly useful for a pilot test, because it allows for various vacuum/flow relationships. A variable speed motor drive, also known as a variable speed drive (VSD) or a variable frequency drive (VFD), allows for precise setting of vacuum, and alters the blower curve in to a "blower map" by "shifting" the blower curve up or down with frequencies less than or slightly greater than 60 Hz. It should be noted that the use of a variable speed drive may invalidate the motor rating for Class I Div I locations (NFPA 70).

(10) Sizing blowers for horizontal vent tests is more difficult due to the complexity of the geometry; however, as a general rule, the target flow rate can be estimated by using the horizontal vent length as the effective vent length ( $L$ ) in Equation 4-1.

(11) Once the blower is selected, the size and capacity of the emissions treatment unit needs to be selected, which governs field logistics at many pilot test sites. Then a test kit can be assembled as shown in Figure 4-6 to conduct the stepped-rate test. The following summarizes the steps required to conduct an example test using the test equipment shown in Figure 4-6. Note that accurate flow rate measurements are critical for a successful pilot test; therefore, use flow measuring devices that are appropriate for SVE (such as pitot tubes or hot-wire anemometers) as described in paragraph 8-3a.

- Connect the intake line from the demister tank to the test vent riser and install monitoring ports as necessary.
- Assemble, erect, and secure the discharge stack from the blower.
- Open completely the dilution valve on the demister tank.
- Connect the power supply to the blower.
- Turn on the blower and measure:
  - Time
  - Flow rate from test vent (should be zero)
  - Flow rate from discharge stack (should be 100 percent blower capacity)
  - Contaminants, lower explosive limit (LEL), etc., of vapor in the vent and discharge stack to establish baseline levels
  - Vacuum at demister tank and test vents (should be approximately zero)

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- Increase the vacuum at the test vent in a series of equal time/vacuum steps by closing the dilution valve on the demister tank. Each step should be long enough to reach steady-state levels (at least 10 minutes) and the dilution valve should be adjusted to maintain a fairly constant ( $\pm 10$  percent) vacuum and flow rate. The vacuum at the test vent should be increased in approximately 5 to 10 equal increments as given by:

$$V_i = i/n (V_{wT}) \quad (4-3)$$

where

$V_i$  = test vent vacuum on the  $i$ th step

$i$  =  $i$ th step in the test

$n$  = total number of steps in the test (5 to 10)

$V_{wT}$  = target maximum vacuum at the test vent, may be maximum available for blower minus losses (e.g., pipe friction)

At the end of each step, measure and record:

- Time
- Flow rates from test vent and discharge stack
- Contaminants, LEL, etc., of vapor recovered from vent and in discharge stack
- Vacuums at demister tank and test vents
- Ambient barometric pressure and temperature
- Once the specified  $V_{wT}$  is reached or the dilution valve is closed completely, decrease the vacuum on the vent in the same increments and repeat monitoring at each descending step until zero vacuum is reached.
- If a variable speed motor drive is used, the procedure is modified by lowering the speed to the lowest recommended (e.g. 45 Hz), closing the dilution valve as discussed above, and then increasing vacuum by increasing the motor speed. This is reversed to step down, decreasing the vacuum.

(12) The ascending stepped-rate test results should be similar to the descending test results and provide a check on the quality of the data. The entire test for a given vent should take several hours to complete.

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(13) The system curve is developed by plotting the well-head flow rates versus the applied vacuum for each step. Figure 4-10 illustrates how to develop the system curve and how the system curve is related to the stepped-test blower curve. Additional system curve points beyond the blower curve can be developed using a larger blower, if necessary.

(14) The precision of the vacuum measurements (i.e., ascending versus descending results) should be equal to about 1/100 of the vacuum on the test vent or 25.4 mm of water vacuum, whichever is greater. The precision of the vapor flow rate measurement should be equal to about 1/5 of the vent flow rate or 0.3 m<sup>3</sup> per minute, whichever is greater.

(15) The test should be terminated immediately and replanned if contaminant levels or other health and safety parameters exceed levels specified in the health and safety plan. It is important to conduct the ascending vacuum test first to evaluate the contaminant levels in the vapors at low flow rates before committing to higher flow rates.

(16) If the  $P_{wr}$  at the test vent is not reached with the dilution valve closed completely, the vent may require retesting with a larger capacity blower. Whether the vent will require retesting in this instance will largely depend on the objectives of the SVE/BV system design.

(17) If the vent straddles or is located just above a water table, the vacuum applied to the vent may pull water into the vent and decrease the effective vent length ( $L$ ). This effect can be severe in some cases and may result in decreasing flow (and increasing amounts of entrained water) with increasing vent vacuums. These effects can be taken into account during the test analysis and do not necessarily indicate that the test results are invalid.

(18) For example, in the case where a vertical vent intersects the water table, the effective screen length is directly dependent on the vacuum on the test vent and is no longer a constant. In this case, the effective screen length in Equation 4-1 can be approximated by:

$$L = L_o - P_w \quad (4-4)$$

where

$$L = \text{effective screen length (cm) at } P_w$$

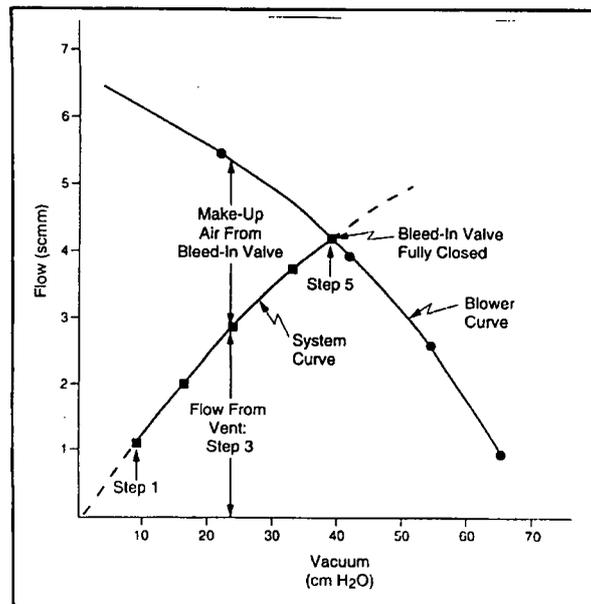


Figure 4-10 Example of system curve construction from stepped rate test

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$L_o$  = antecedent effective screen length (cm) (i.e., at  $P_w = P_A$ )

$P_w$  = observed vacuum at test vent (cm<sup>water</sup>) (corrected for vacuum loss along well screen and casing, if vacuum is measured at well head)

(19) If the initial, effective screen length ( $L_o$ ) is fairly short, the maximum flow rates will be achieved at relatively low vacuums and the vent may not be useable for the full-scale SVE/BV system.

(20) To monitor the elevation of the liquid level in a vertical vent well, it is necessary to zero a pressure-sensing device mounted at a known depth below ground surface in the well to the vacuum in the air above the liquid (Figure 4-11). Typically a pressure transducer is installed in the well and connected to a data logger via a cable that contains an air tube by which the transducer is referenced to the well vacuum. Using the equations shown in Figure 4-11, the height of upwelling,  $Z_{up}$  is calculated as  $Z_{up} = h_{up} - h_{wt}$ . It is important that the transducer be referenced to the well vacuum rather than atmospheric pressure as is normally done. If the reference pressure is atmospheric pressure the transducer will indicate the piezometric surface but not the actual elevation of the water table in response to upwelling. Another means of accomplishing this would be to reference the pressure transducer to atmospheric pressure while obtaining a separate measurement of well vacuum (also referenced to atmospheric pressure) to use for the differential pressure calculation ( $P_w - P_{up}$ ) (Figure 4-11).

(21) A relatively low-cost alternative technique suitable for spot checks is to employ a 0.6-cm copper bubbler tube installed and sealed through the well cap and extended within the well casing down to a known elevation below the lowest expected elevation of the water table (personal communication w/James Hartley and William Miller, CH2M Hill, Sacramento, CA). The top of the copper tube is connected to one side of a differential magnehelic gauge, while the other side of the gauge is connected to the well casing so as to sense the well vacuum. Each time the actual water level needs to be measured, an operator must use a small hand-operated air pump on the tube side of the gauge to gradually pressurize the tube, displacing the water column from the bottom of the tube while observing the associated rise in pressure on the gauge. When all the water has been displaced from the tube, additional air pumped into it will bubble through the water, and no additional rise in pressure will be observed on the gauge. The resulting maximum differential pressure measured on the gauge is equivalent to ( $P_w - P_{up}$ ) (Figure 4-11). It is important to provide a fitting on the tube that permits the air pump to be connected to it without allowing outside air to enter the tube prior to pressurization. If it did, the water level within the tube would fall as it equilibrates with atmospheric pressure, leaving less of a water column to displace. Thus the actual extent of upwelling would be underestimated.

(22) Methods that enable the extent of upwelling to be determined and that incorporate evaluation of the thickness of the capillary fringe include: use of a neutron moisture meter, time domain reflectometry (TDR), capacitance probes or buried resistance blocks. Applicable methods are specified in Chapter 3 of this EM, Table 3-2 of EM 1110-1-4010, and Chapter 3 of EM 1110-1-4005.

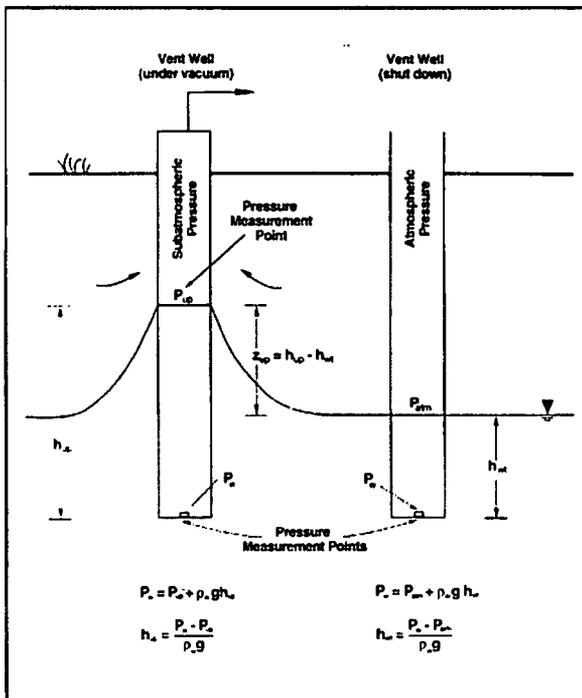


Figure 4-11 Monitoring upwelling

f. *Constant-rate performance tests for vent areas of influence and efficiencies.* Constant-rate performance tests can be conducted on either horizontal or vertical vents and are used primarily to evaluate areas of influence for various vent geometries and configurations. Constant-rate tests are also used to evaluate vent efficiencies and can incorporate the air permeability test. Lastly, long-term constant rate tests can be used as a basis for extrapolation of contaminant concentrations at later times for design of more efficient offgas treatment systems and for evaluating clean up effectiveness. Again, the constant rate testing can be conducted as a first phase of a full-scale implementation of SVE at a site.

(1) The vent is tested at the highest flow rate obtainable with a test blower as determined by a stepped-rate test (see paragraph 4-5e), and the resulting subsurface vacuums are measured at several observation points distributed around the test vent. These monitoring points are often efficiently installed by direct push methods. However, the designer should be aware of the limitations of direct push installation, as discussed in paragraph 5-5b.

(2) The resultant vacuum/pressure data are usually plotted and mapped in plan and cross-section view to evaluate the extent and shape of the area of vacuum/pressure influence of the vent, as well as the vacuum losses attributable to the vent itself (i.e., efficiency). The distribution of vacuum and flow observed during the constant rate test can illuminate much about the heterogeneity and complexity of a site. Figures 4-12 and 4-13 provide example results for constant-rate area of vacuum/pressure influence tests on a vertical and a horizontal vent, respectively. Examples of vacuum measurements with distance from test SVE well are presented in Figure 4-14. To reiterate, however, the observed vacuum distribution should not be used as the basis for full-scale wellfield design unless vapor capture is the objective.

(3) Using the vacuum influence measurements around the SVE well, a vacuum distribution is developed and a site specific air permeability value is developed. Using the air permeability, estimates of pore gas velocity (i.e., specific discharge) can be made for a given SVE extraction flow rate.

(4) The following paragraphs briefly summarize the steps required to conduct a typical constant-rate performance test. Additional procedures for conducting pilot SVE/BV tests are provided in Appendix D.

- Assemble and connect the test equipment to the vent as described in paragraph 4-5c (see also Figure 4-6).
- Turn on the blower and close the dilution valve on the demister tank until the maximum flow rate is reached.

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(a) To determine air permeability using the pseudo-steady state analysis (assuming two-dimensional flow), the minimum duration for the test can be calculated according to:

$$T_s = (r^2 n_a \mu_a) / (0.04 k_a P_{atm}) \quad (4-5)$$

where

$P_{atm}$  = atmospheric pressure

$T_s$  = time to reach pseudo-steady state conditions, and

$r$  = the radial distance to the outermost observation well for which data are required.

(b) If a transient analysis will be performed using the Cooper-Jacob approximation, only data from times greater than  $T_s$  may be used. Pressure measurements should reach a nearly steady-state condition at 10 to 100 times  $T_s$  (Johnson, Kemblowski, and Colthart 1990b).

- The air permeability ( $k_a$ ) and effective soil porosity ( $n_a$ ) can be estimated as described in paragraph 4-5e(6). Generally, it takes a few hours to a few days for vacuums to stabilize at the limits of the area of vacuum/pressure influence.
- Monitoring of barometric pressure before and during the test is important because noise associated with barometric pressure fluctuations can otherwise obscure the desired vacuum signal. Diurnal barometric pressure changes in soil can be on the order of a few mbar (Massmann and Farrier, 1992), whereas 0.1 inch water vacuum (the value often adopted by ROI practitioners as indicative of significant vacuum) is equivalent to only 0.25 mbar. Thus natural pressure gradients can overwhelm the smaller pressure gradients exerted at a distance from venting wells. By monitoring the barometric pressure during the test, the gauge pressure/vacuum can be corrected for the variation in atmospheric pressure.
- Periodic measurement of the contaminant concentrations in the influent throughout the test may provide information on the rate of decay of the concentrations over longer time. This information is useful for projecting treatment costs and designing offgas treatment systems.
- Once the vacuums at the observation vents have stabilized, measure and record:
  - Time
  - Vacuum at observation vents
  - Flow rates from vent and discharge stack
  - Contaminants, LEL, etc., in vent discharge and discharge stack
  - Ambient barometric pressure and temperature

- Turn off the blower and record the recovery in the observation and test vents.

(5) The success of any constant-rate performance test will partially depend on the distribution of the monitoring points with respect to the test vents. Therefore, vacuums should be measured at the monitoring points during the stepped-rate tests (see paragraph 4-5e) to determine whether additional points are required to adequately establish the vacuum response over the target pilot test area. This may be important if site heterogeneity must be evaluated or if the vacuum response in the available monitoring points is small.

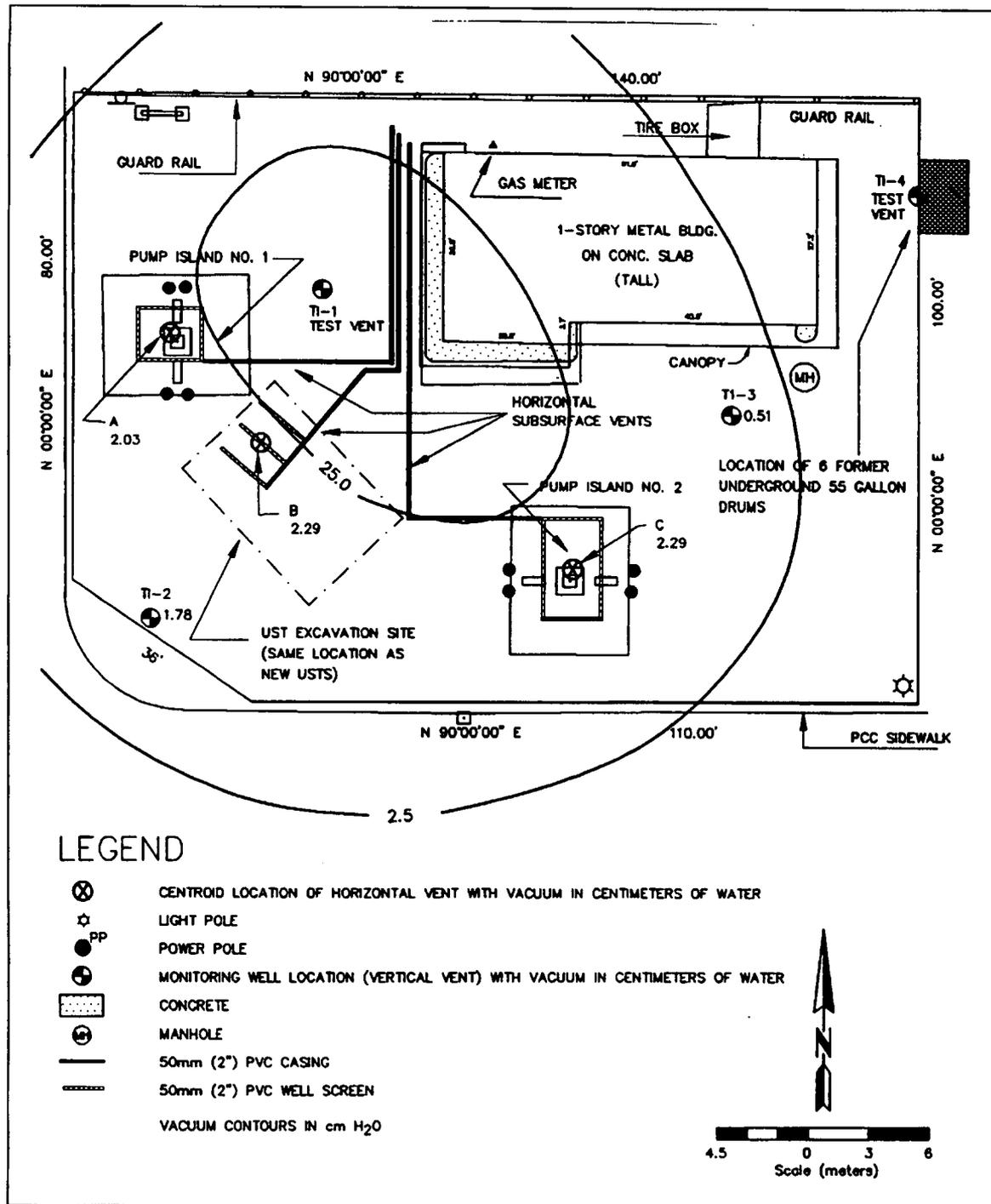


Figure 4-12 Example vacuum map for constant-rate test, vertical vent

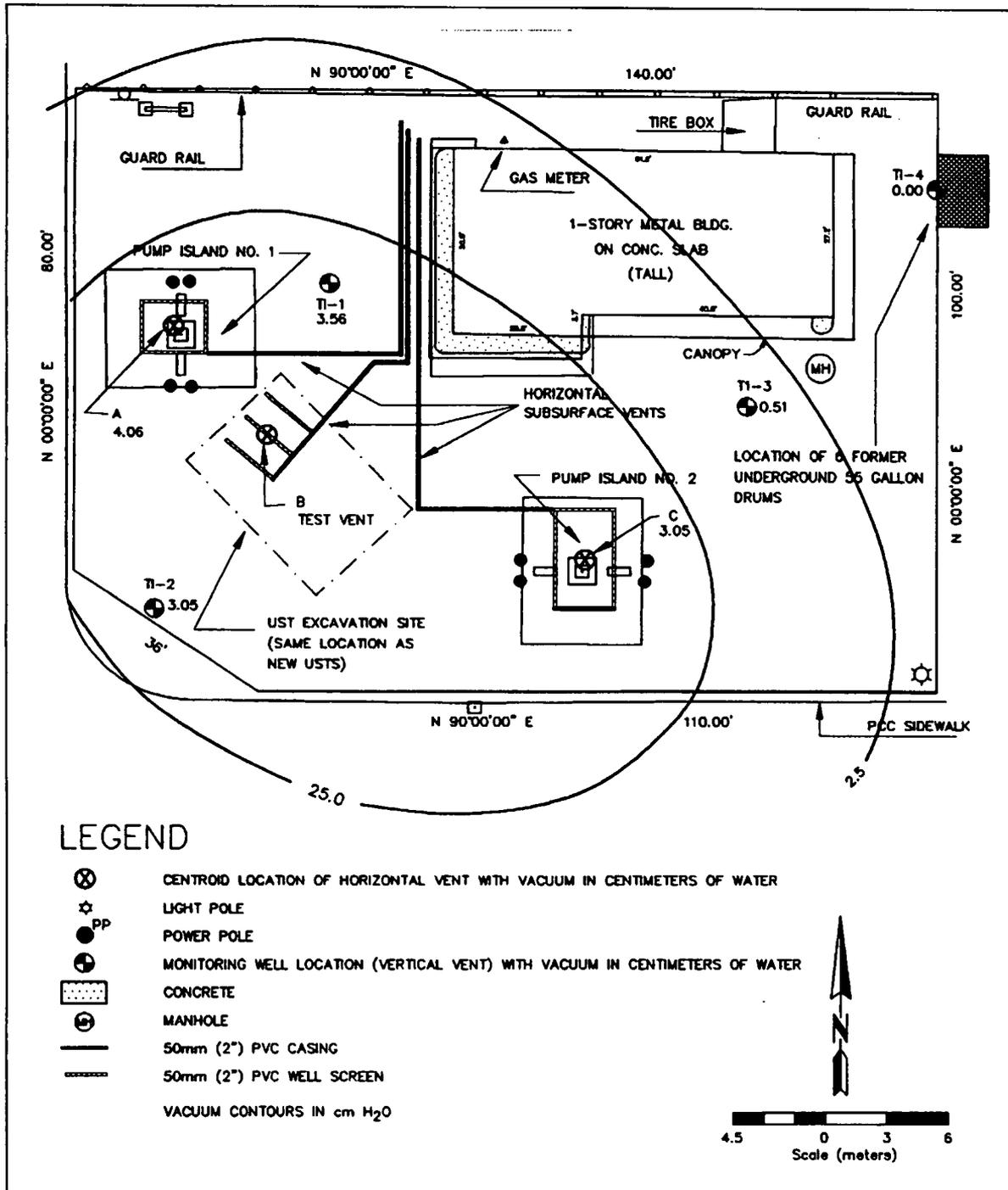


Figure 4-13 Example vacuum map for constant-rate test, horizontal vent

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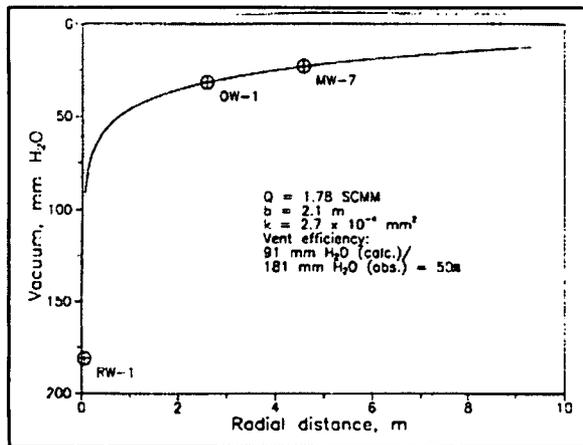


Figure 4-14 Steady-state pump test

(6) Vent efficiency is defined as

$$E = V_{ro} / V_w \quad (4-6)$$

where

 $E$  = efficiency (dimensionless) $V_{ro}$  = vacuum just outside the test vent (at radial distance  $\sim r_o \approx R_w$ ) in cm of water $V_w$  = measured vacuum at the test well head in cm of water

(7) The efficiency of the vent indicates how much vacuum is lost due to flow through the well screen and annular packing and up the well itself. Efficiency is defined as the ratio (expressed as a percentage) of the vacuum inside the well to just outside the vicinity of the borehole and are quite variable depending on the site moisture conditions, drilling methods, and well materials. Moisture migration toward the well, use of drilling fluids in drilling, and use of screen with little open area (i.e. slotted pipe) contribute to low well efficiency. Vent efficiency in SVE/BV is analogous to water well efficiency.

(8) The efficiency of a vent can be estimated by directly observing the vacuum lost between the vent and the soil adjacent to the vent. This can be accomplished in a number of ways, including

- Installing a small-diameter piezometer in the annulus of a vertical vent.
- Installing observation vents directly adjacent to the vertical or horizontal vent (within a few centimeters of the annulus).

(9) Either of these methods is effective; however, installing one piezometer in the annulus is generally less expensive than installing observation vents.

(10) Vent efficiencies can also be estimated by comparing the measured vacuum in the test vent to the theoretical vacuums, predicted by the steady-state radial flow models. The ratio between the predicted vacuum of the test vent (i.e., radial distance  $R_w$ ) and the actual, measured vacuum in the test vent provides one estimate of the vent efficiency. If a vent is 100 percent efficient (no head losses), the predicted and actual vacuums should be the same. An example graph illustrating vent efficiency estimated by this method is shown in Figure 4-14.

(11) The predicted pressure at a vertical vent using the steady-state radial flow solution for a homogeneous soil is

$$P_{wp} = \left\{ \frac{\left[ \frac{\ln(r_o / R_w)}{\ln(R_I / R_w)} \right] P_A^2 - P_{ro}^2}{\left[ \frac{\ln(r_o / R_w)}{\ln(R_I / R_w)} \right] - 1} \right\}^{1/2} \quad (4-7)$$

where

$P_{wp}$  = predicted absolute pressure at the test vent ( $\text{g/cm}\cdot\text{sec}^2$ )

$r_o$  = radial distance of an observation vent within the area of influence of the test vent from the test vent (cm)

$R_I$  = radius of influence of the test vent (i.e., the distance where  $P = P_A$ ) (cm)

$P_A$  = absolute atmospheric pressure ( $\sim 1.01 \times 10^6 \text{ g/cm}\cdot\text{sec}^2$ )

Other terms are defined in Equation 4-1.  $R_I$  can be estimated from the extent of observed vacuums in the observation vents. It should be noted that these equations are based on confined flow assumptions. There may be errors (perhaps large) if they are applied to open sites.

(12) If two observation vents are within the area of influence but at different radial distances from the vertical test vent at a covered site, an alternative version of the steady-state radial flow equation can be used to predict the pressure at the test vent even though  $R_I$  is unknown:

$$P_{wp} = \left[ \frac{\ln(r_2 / R_w) P_{r1}^2 - \ln(r_1 / R_w) P_{r2}^2}{\ln(r_2 / r_1)} \right]^{1/2} \quad (4-8)$$

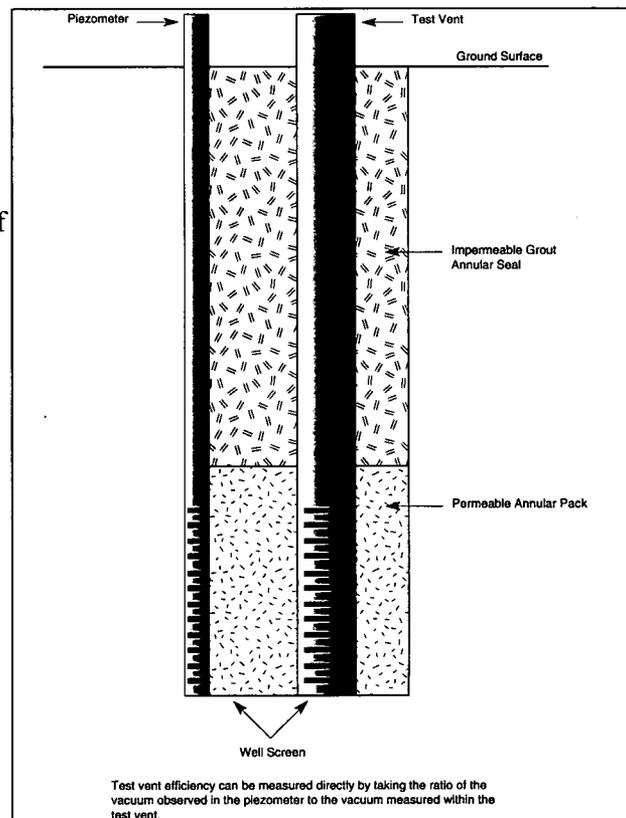


Figure 4-15 Test vent well design.

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where

$P_{wp}$  = predicted absolute pressure at test vent (distance  $R_t$ , g/cm·sec<sup>2</sup>)

$P_{r1}$  = absolute pressure at observation vent 1 (g/cm·sec<sup>2</sup>)

$P_{r2}$  = absolute pressure at observation vent 2 (g/cm·sec<sup>2</sup>)

$r_1$  = radial distance (cm) of observation vent 1 from test vent

$r_2$  = radial distance (cm) of observation vent 2 from test vent

$R_w$  = radius of test vent (cm)

$r_1 < r_2$

(13) In the example (Figure 4-14), the vertical vent well had an efficiency of 0.50, which is within the typical range of 0.2 to 0.8 for 50- to 101-mm (2-inch to 4-inch) ID vertical vents with slotted well screens. It is unlikely that poor vent efficiency is caused by inertial forces near the vent screen or annular packing. Even in extreme cases where a vent is screened in coarse-grained soil and vapors are recovered at high rates, it is unlikely that turbulent flow conditions are achieved near the screen (Beckett and Huntley 1994). Thus, one would not expect to observe a simple quadratic correlation between vent efficiency and vapor flow velocities under typical applications. Increased water saturations and the associated drop in air permeability around the vent can, however, result in dramatic head losses adjacent to the vent. These head losses are manifested as poor vent efficiency. These effects are discussed by McWhorter (1990) and in paragraph D-5.

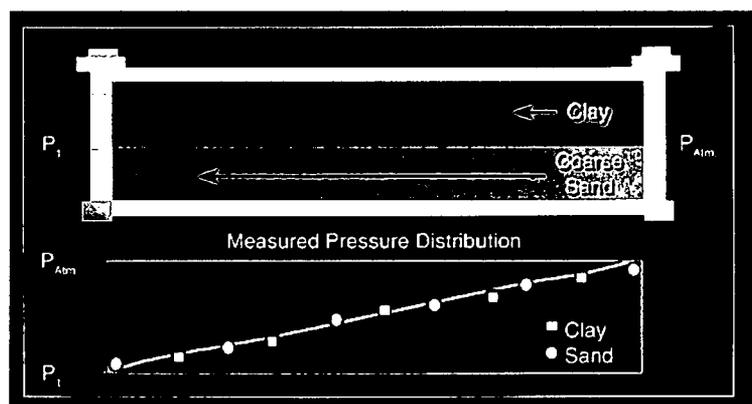
(14) It is important to account for observed vent efficiencies in interpreting performance and other test results (i.e., permeability tests). For example, an inefficient vent well can lead to underestimates of soil air permeability and radii of influence, and may lead one to conclude erroneously that a site is not amenable to SVE/BV remediation. The data presented in paragraph 4-8 may have been strongly influenced by such effects.

(15) The radius of pressure influence ( $R_i$ ) of the test vent can be estimated directly from the contour maps of the observation vent vacuums (see for example Figures 4-12 and 4-13). The radius of pressure influence can also be estimated using various steady-state flow models. The observed (i.e., mapped) and calculated radii of pressure influence can then be compared to evaluate the applicability and adequacy of the flow models and to aid in interpreting the data. **The radius of pressure influence is not appropriate as a basis for selecting vent spacing**, except perhaps for systems intended to capture vapors to prevent lateral migration from a source.

(16) In the example vent (Figure 4-12), the calculated  $R_i$  was about 21.3 m and was consistent with the observed vacuums. In the example, the agreement between predicted and observed effects was adequate to use radial steady-state flow models to design an SVE/BV system for the site without significant additional

testing. This design is not based on radius of vacuum influence, but rather specific discharge calculated using the observed vacuum distribution and the soil air permeability.

(17) In many of the previous paragraphs, the reader has been cautioned regarding the inappropriate use of predictive equations assuming purely horizontal radial flow and the dangers in using the radius of pressure influence for aspects of design. The radius of pressure influence is based on the theoretical limit of vacuum effects for an SVE/BV vent. This theoretical parameter is important because the  $R_f$  is included in the boundary conditions for two-dimensional radial vapor flow models. Vacuums below 0.02 cm of water are difficult to measure, which limits the ability to determine the true radius of influence of a vent. Some workers have arbitrarily defined the radius of pressure influence at a specific pressure head to address this limitation (Buscheck and Pearnin 1991).



**Figure 4-16** Steady-state pressure distribution for 1-D flow between parallel trenches installed in confined layers. Lengths of horizontal arrows indicate relative air velocity. Note that measurable pressure/vacuum readings are no guarantee of significant vapor flow rates (after Johnson and Ettinger, 1994)

(18) Given that vacuum is independent of permeability, an arbitrary definition of radius of pressure influence based on vacuum or pressure head is not a good indicator of treatment zone. The radius of vacuum/pressure influence does not provide, in most cases, an estimate of the zone of effective air exchange of the vent (Johnson and Ettinger 1994; Beckett and Huntley 1994; King 1968; Shan, Falta, and Javandel 1992), which is often much smaller than the radius of pressure influence. The zone of effective air exchange for a vent should represent the area that can be effectively remediated by the vent in a required time. Because the efficiency of SVE/BV is usually evaluated in terms of the total time required for remediation, treatment time should be considered when evaluating the zone of effective air exchange (refer to paragraph 5-3). Treatment time is dependent upon the contaminant removal rate, which is partially dependent on the vapor flow rate. Other variables affecting the contaminant removal rate include airflow paths, flow velocities, travel times, and contaminant retardation. Vapor velocity at a given vacuum depends on air conductivity, as illustrated in Figure 4-15. Measurable vacuum does not imply velocities high enough to accomplish remediation in a timely fashion.

(19) Airflow paths represent the course that air follows during migration toward an extraction vent. At the macroscopic scale, flow paths are described by streamlines, which are drawn perpendicular to equipotential lines such as those shown in Figure 2-7. Since streamlines are everywhere parallel to the direction of airflow, the macroscopic flow velocity can be calculated along a streamline using Darcy's law (Equation 2-11). The microscopic flow velocity  $q_s$  (also known as the seepage velocity) can be calculated according to

$$q_s = \frac{k_a dP}{\mu n_a ds} \quad (4-10)$$

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where

$dP/ds$  = the pressure gradient (change in pressure with change in distance) along a streamline

(20) At the macroscopic scale, travel times can be used to evaluate the rate of air exchange. Travel time can be calculated by integration of the macroscopic flow velocity along a streamline (e.g., King 1968; Shan, Falta, and Javandel 1992). Travel time can be plotted versus distance from an extraction vent to evaluate the time required to withdraw contaminated vapor. For two-dimensional radial flow, the assumption of incompressibility makes calculation of travel times simply:

$$t = \frac{\pi r^2 b n_a}{Q} \quad (4-11)$$

where

$t$  = travel time

$r$  = radial distance

(21) Travel times can be computed for more complex geometries and boundary conditions by numerically integrating the inverse of the air velocity (the product of the air conductivity and pressure gradient divided by the average porosity) over distance along each streamline from the surface or other air source to the vent well. Air exchange rates (pore volumes per time) through the streamtubes bounded by the streamlines are the inverse of the travel times.

*g. Vertical profiling to develop an accurate 3-dimensional conceptual model of the vadose zone.* Recently, a pneumatic well logging technique, termed PneuLog®, has been developed that can simultaneously measure cumulative gas flow and contaminant concentrations along the length of a vent well screen during SVE (Praxis Environmental Technologies, 1999). Pneumatic logging is conducted using a downhole gas velocity sensor that is first lowered into the vent well and then is raised at a steady rate from the bottom to the top of the well screen while gas is being extracted from the well. A special wellhead assembly enables this measurement to be accomplished without interfering with the application of vacuum to the well. Using this technique, a profile of the vertical distribution of contaminant extraction rates and air flow rates is developed for the vadose zone soils. These data can then be used to develop estimates of air permeability for different depth intervals / soil strata. Proper use of this information allows the SVE practitioner to optimize the location of vent wells and optimize screen placement to target the contaminant-producing soil layer. During vertical profiling of flow from the vent well, the change in cumulative gas flow measured by the velocity sensor as it travels from one depth interval to another (Figure 4-17a) is equal to the gas flow emanating from that soil interval. The  $k_a$  value for each interval is then determined from Darcy's Law. Typical cumulative flow data appear similar to output from spinner testing in water wells and the data analysis is identical (Molz et al., 1989). The technique is analogous to techniques applied in water wells to identify preferential pathways for groundwater (Young, 1995; Paillet, 1998). When vertical pneumatic logging is conducted while simultaneously measuring soil gas pressures in monitoring points within the formation around the well, the technique is capable of yielding better gas permeability data than conventional methods because both of the components of gas permeability, the gas flow and the pressure gradient are measured as functions of depth. Thus, the vertical variation in  $k_a$  within the formation is revealed (Figure 4-17b).

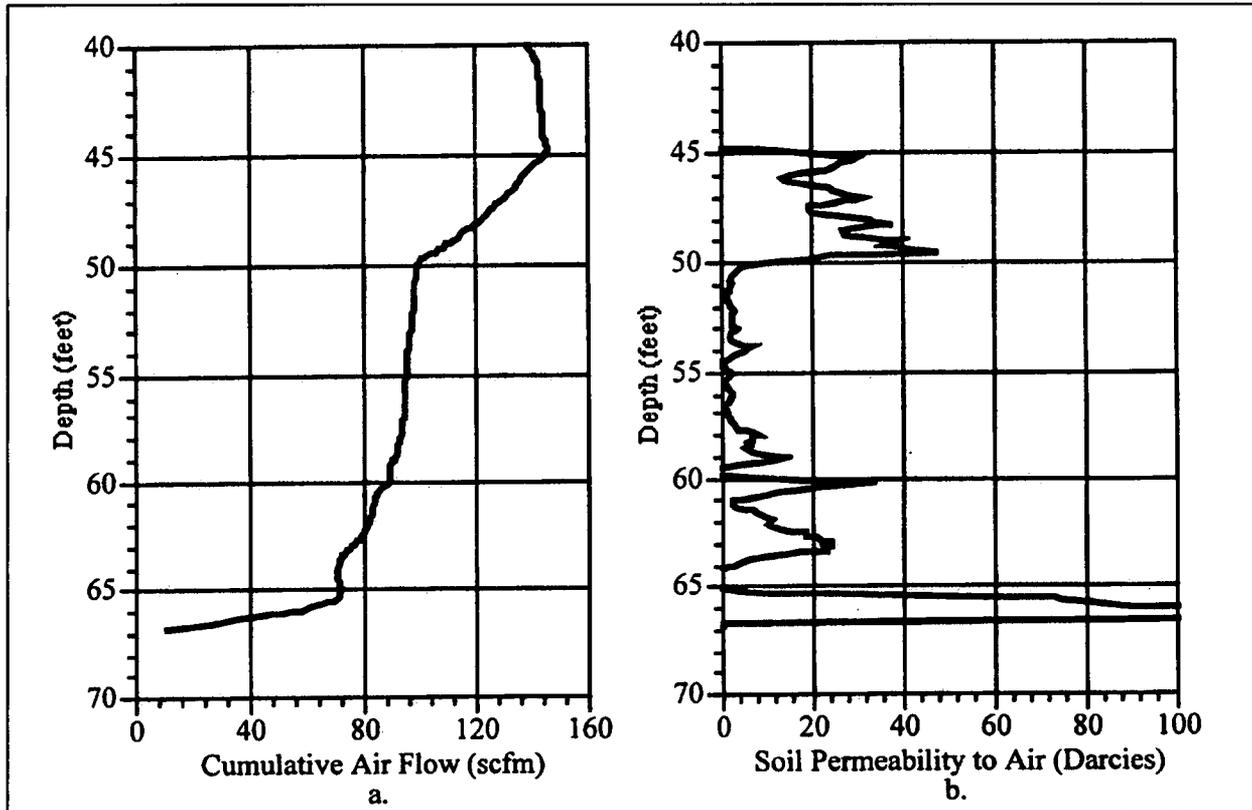


Figure 4-17 Example pneumatic well logging results for soil permeability to air. (Figure provided courtesy of Praxis Environmental Technologies, Burlingame, CA.)

#### 4-6. Minimum Test Report Outline

This section presents a generic outline for the development of pilot- or bench-scale test reports. The topics outlined below represent the minimum information needed for a useful report. Additional site-specifics and system details may be provided where applicable. Items marked with an asterisk (\*) may not be applicable for bench-scale column tests. Alternative topics for these items are included in parentheses where applicable.

- I. Introduction
  - A. Background
  - B. Objectives

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**II. Equipment**

**A. Wells and Piping\* (Experimental Setup)**

1. Extraction Wells
2. Monitoring Wells

**B. Vapor Collection System**

1. Blower System

**C. Vapor Pretreatment System**

1. Air-Water Separator
2. Particle Filter
3. Other Pretreatment Equipment

**D. Vapor Treatment System**

**E. Ancillary Systems**

**F. Monitoring Equipment and Instrumentation**

**III. Monitoring and Data Collection**

**A. Chemical Concentration**

**B. Temperature**

**C. Pressure/Vacuum**

**D. Flow Rate**

**E. Departures/Exceptions to the Work Plan**

IV. Results and Discussion

A. Physical Parameters

1. Air Permeability
2. Vacuum/Pressure Distribution and Radius of Effective Air Exchange
3. Vacuum/Flow Rate Correlation

B. Chemical Parameters

1. Extracted Soil Vapor
2. Treated Soil Vapor
3. Residual Soil
4. Recovered Condensate
5. Chemical Data Quality

V. Conclusions and Recommendations

- A. Overall Effectiveness of Technology
- B. Needs for Further Study
- C. Conceptual Final Design of Full-Scale System\*

Appendices

- A. Laboratory Analysis Reports
- B. Quality Assurance Reports
- C. System Parameter Monitoring Sheets
- D. Well Installation and Boring Logs\*

#### 4-7. Examples of Bench- and Pilot-Scale Test Reports

This section contains a number of different examples that detail the procedures and results of various bench- and pilot-scale SVE/BV tests. In the interest of conciseness, the test reports provide only the salient data and results that set that particular test apart from the others. The following tests are described:

- Bench-Scale Column Study.
- Air Permeability Test.
- Blower Step Test.
- Air Respiration Test.

*a. Bench-scale column study.*

(1) Test description.

(a) A bench-scale laboratory column study was performed on a soil sample collected at a site contaminated with PCE (Ball and Wolf 1990). The purpose of the test was to provide additional data on: 1) achievable soil cleanup levels by SVE; and 2) estimated emission concentrations in the extracted soil vapor (see also paragraph 4-2a).

(b) The soil boring was completed in the vicinity of the highest known PCE soil concentration at the site. A split spoon soil sample was collected at a depth of 1.2 to 2.0 meters and placed in a pre-cleaned, 2-liter glass jar with a Teflon-lined cap.

(c) During the column test, 0.8 liter per minute of air was passed through the soil column, and the pressure drop across the soil column was measured to determine the air permeability. The soil was analyzed for VOCs before and after the column test by USEPA Method 5030/8240. The exhaust air was analyzed for VOCs by GC/MS to quantify and identify the VOCs. PCE was found to be the only volatile constituent in either the soil or the vapor.

(2) Test procedure.

(a) The test soil was packed into a 76.2-mm (3-in.) I.D. by 304.8-mm long Teflon/plastic tube in 25.4-mm (1-in.) layers. Each layer was tamped to achieve a bulk density consistent with field measurements. Assuming 20% air-filled porosity, this represents approximately 0.3 L of air in the column. Manometers were attached to the inlet and outlet of the soil column, along with the necessary piping, measuring devices, and vapor treatment apparatus. Compressed air was then introduced to the column base at a flow rate of 0.8 liter per minute (lpm). The pressure drop across the soil was then measured at 1.8 cm H<sub>2</sub>O. Table 4-4 lists these data as well as other environmental parameters that were measured at the start of the test.

(b) The vapor stream was sampled on an increasing time schedule as it exited the soil column. The samples were collected using an airtight syringe for direct injection to the GC. A total of 12 vapor samples

were collected over a period of 10 days, although the first 11 samples were taken during the first two days. Figure 4-18 presents a plot of the PCE concentrations over time. Note that during the 10-day test over 38,000 pore volumes of air passed through the column.

(c) At the end of the 10-day test, a core was collected from the soil column and analyzed for VOCs by the 5030/8240 method. The results of this analysis were compared with those from the pretest soil sample.

### (3) Results and discussion.

(a) The concentrations of PCE in the pretest and post-test soil samples were 0.500 ppm and 0.07 ppm, respectively, indicating an 86 percent removal over the 10-day test. However, due to heterogeneities and the fact that the soil samples were very small in relation to the total amount of soil in the column (0.005 kg versus 2.34 kg), a better approximation of the initial soil concentration was determined by integrating the curve shown in Figure 4-18. This method led to a pretest PCE concentration of 13 ppm, which is very close to the 12.5 ppm site-wide average concentration found during a previous soil investigation. The 13-ppm estimate indicates a removal of greater than 99 percent was achieved during the test. Irrespective of the method used to calculate mass removal, an 86 percent or greater PCE removal was obtained during the column test. These values confirm the feasibility of SVE in remediating the unsaturated soils at the site.

(b) Figure 4-18 shows an average exhaust vapor concentration during the early part of the test of 0.012 mg/l. Over time, however, that average is expected to diminish as the concentrations approach asymptotic values much below 0.012 mg/l, as Figure 4-18 demonstrates. The 0.012-mg/l value can be used as a maximum expected concentration when sizing potential emissions control systems and when applying for an air permit.

**Table 4-4**

**Column Test Data**

**Soil Sample**

| Mass (g) | Area (cm <sup>2</sup> ) | Height (cm) | Density (g/cm <sup>3</sup> ) | Temp (°C) |
|----------|-------------------------|-------------|------------------------------|-----------|
| 2340     | 45.6                    | 30.5        | 1.67                         | 18.20     |

**Test Conditions**

| Airflow Rate (cm <sup>3</sup> /min) | Air Loading Rate (cm <sup>3</sup> /cm <sup>2</sup> -min) | Inlet Pressure (cm H <sub>2</sub> O) | Outlet Pressure (cm H <sub>2</sub> O) | Pressure Drop (cm H <sub>2</sub> O) |
|-------------------------------------|--|--------------------------------------|---------------------------------------|-------------------------------------|
| 800                                 | 17.54  | 1,024.5                              | 1,022.7                               | 1.8                                 |

Temp. of Inlet Air = 20°C

Relative Humidity of Inlet Air - 21%

Initial Soil Moisture Content = 8.6% (weight)

Final Soil Moisture Content = 3.6% (weight)

Test Duration = 240 hours

**PCE Data**

| Integration of Figure 4-18 (ppm) | EPA Method 5030/8240 |             |
|----------------------------------|----------------------|-------------|
|                                  | Initial (ppm)        | Final (ppm) |
| 13.0                             | 0.500                | 0.070       |

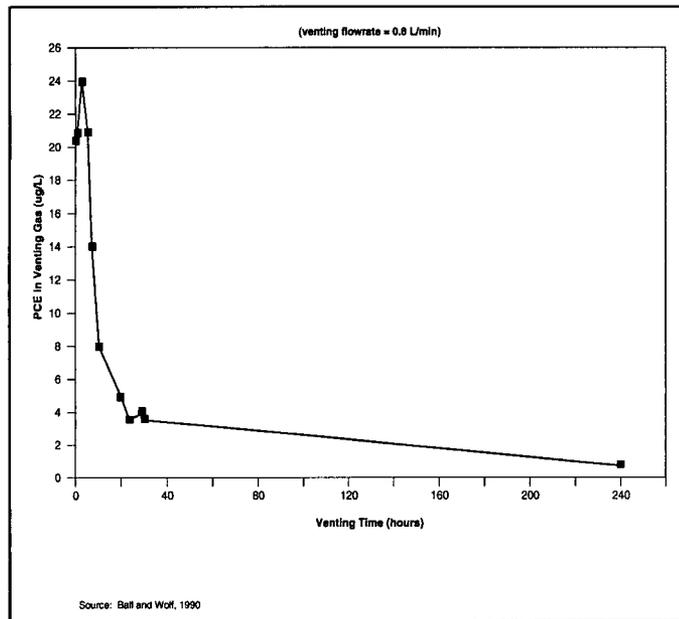


Figure 4-18 Tetrachloroethylene (PCE) venting curve

*b. Air permeability test.*

(1) Air permeability is perhaps the most important soil parameter to be considered in the successful application of SVE (Johnson, Kemblowski, and Colthart 1990b) and is also important for BV (Hinchee and Leeson, 1995). The air permeability at a site with an extensive impermeable surface cover was determined by extracting 2.65 scmm from a single vent well and monitoring three vacuum monitoring probes for an hour. The vacuum measurements from each probe are plotted in Figure 4-19. The method of analysis presented in Johnson, Kemblowski, and Colhart (1990b) was used to determine the air permeability at the site. Refer to Appendix D for the equations used. The HyperVentilate or VENTING software (USEPA 1993c) provides a means to quickly determine the air permeability for covered sites by numerically fitting a line to the semi-log plot of the data and solving these equations. The air permeability estimates from the analysis are provided below:

(c) Figure 4-18 is typical in shape of the curves expected from a full-scale SVE system. The decreasing slope (indicating mass removal rate) is primarily due to two effects: 1) the diminishing mass transfer of the PCE from the soil and liquid phases into the vapor phase; and 2) the diluting effect of the airflow, which implies that as concentrations diminish in a constant vapor flow rate, the mass removal rate must also diminish. The curve of vapor concentrations versus time obtained from the column test was a good predictor of full-scale performance at this relatively homogeneous, sandy site (Ball and Wolf 1990; Urban 1992).

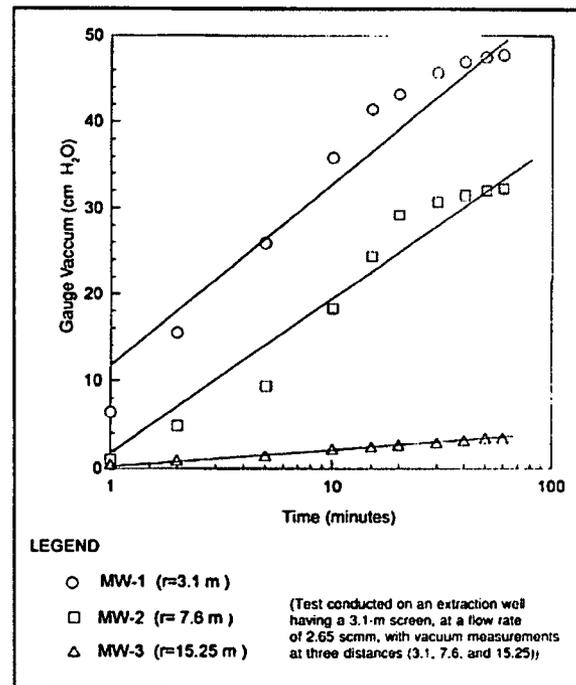


Figure 4-19 Semi-log plot of vacuum versus time for air permeability test

| Monitoring Well | Permeability (darcies) |          |
|-----------------|------------------------|----------|
|                 | Method A               | Method B |
| MW-1            | 16.44                  | 8.83     |
| MW-2            | 20.01                  | 14.08    |
| MW-3            | 223.3                  | 121.1    |

(2) Upon inspection of Figure 4-19, it is apparent that the slopes of the lines for MW-1 and MW-2 are very similar. Since  $k_a$  is proportional to the slope of the line, it follows that the permeabilities are nearly equal for those two wells, indicating a fair degree of homogeneity. The slope of the line for MW-3, however, is much less, indicating an increase in permeability due to a change in soil conditions between 7.5 and 15 meters away from the extraction well. Additional data points, at various orientations to the extraction well, would be needed to determine whether the increase in permeability is due to a change in soil conditions or due to entry of air from the surface between MW-2 and MW-3.

c. *Step test.* The purpose of the step test was to establish vacuum/flow rate relationships and to examine well efficiencies over the range of extraction rates. Efficiency refers to the pressure drop across the well screen with respect to various flow velocities. As the flow rate through the well screen increases, so does the pressure drop across the well screen. A well is considered inefficient when the flow capacity of the well is significantly reduced because of the pressure drop across the well screen (see also paragraph 4-5f).

(1) In this example, vacuum was measured at the wellhead using a Magnehelic® gauge, and flow rate was measured using an in-line pitot tube flow meter.

(2) The step test was conducted over a period of one day, during which the vacuum conditions were stepped up from 50.8 to 254 mm Hg. Each vacuum was applied for two hours, allowing sufficient time for conditions to equilibrate. Table 4-5 and Figure 4-20 show the vacuums and their associated flow rates at the end of each two-hour period.

(3) In order to evaluate the well efficiencies at the various vacuum/flow conditions, the flow rate was divided by the wellhead vacuum. Figure 4-21 presents these data, known as the specific capacity, as a function of the wellhead vacuum. The slightly downward slope of the curve is due to the fact that the well losses are proportional to the square of the vapor velocity through the well screen. This effect is expected to become greater as vacuums increase further.

**Table 4-5**  
**Step Test Data**

| Vacuum at Wellhead, Vw (mmHg) | Extraction Rate, Q (scmm) | Specific Capacity, Vw (scmm/mmHg) | Vacuum at R = 3.05m (cm. H <sub>2</sub> O) | Vacuum at R = 6.10m (cm. H <sub>2</sub> O) | Vacuum at R = 12.20m (cm. H <sub>2</sub> O) |
|-------------------------------|---------------------------|-----------------------------------|--|--|---|
| 50.8                          | 1.783                     | 0.035                             | 4.829                                      | 3.048                                      | 2.286                                       |
| 101.6                         | 3.40                      | 0.033                             | 8.382                                      | 6.096                                      | 4.57  |
| 152.4                         | 4.58                      | 0.030                             | 11.68                                      | 9.398                                      | 6.35  |
| 203.2                         | 5.236                     | 0.026                             | 15.24                                      | 12.19                                      | 8.128                                       |
| 254                           | 5.38                      | 0.021                             | 18.542                                     | 14.48                                      | 9.906                                       |

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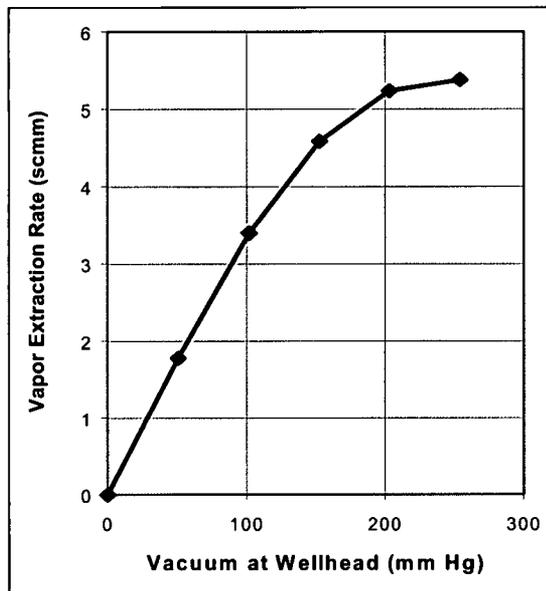


Figure 4-20 Specific capacity versus vacuum

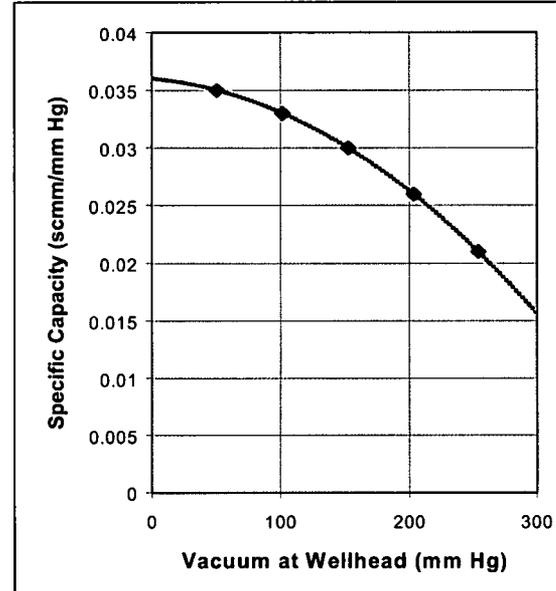


Figure 4-21 Extraction rate versus vacuum

*d. Air respiration test.* In situ air respiration tests are used to provide rapid field measurement of in situ biodegradation rates. Hinchee et al. (1992) have developed a test protocol for the U.S. Air Force that has been used at many BV sites in the United States (see paragraphs 3-4 and 4-2d). This test protocol has been adopted as part of AFCEE's Bioventing Design process and has been endorsed by U.S. EPA in their manual on Bioventing Principles and Practice (Volume II, Leeson and Hinchee, 1995).

(1) The test consists of injecting air and an inert tracer gas (typically helium) into the vadose zone in the area of highest VOC contamination, as well as in an uncontaminated background location having similar soil properties. The air provides oxygen to the soil, while the inert gas provides data on the escape of the injected air away from the injection point, either through the diffusion of air away from the ground surface and the surrounding soil, or through leakage from a poorly sealed well. The tracer gas also allows verification that the soil gas sampling system does not leak.

(2) After a given period of time, in the case of this example 24 hours, the gas injection was stopped, and concentrations of  $O_2$ ,  $CO_2$ , and the tracer gas were monitored for the next 50 hours. Initially, readings were taken every 2 hours, but the interval increased to as high as 9 hours overnight. Concentrations of  $O_2$  and  $CO_2$  were compared with those measured before the injection began.

(3) Test implementation.

(a) Air with 1 to 2 percent helium was injected into four monitoring wells and one background well. Oxygen utilization rates were determined from the data obtained during the BV tests. The rates were calculated as the percentage change in O<sub>2</sub> over time. Figure 4-22 and Table 4-6 show the graphic and tabular forms of the data, which showed an oxygen utilization rate of -5 percent per day (-0.23 %/hr). The straight-line reduction in O<sub>2</sub> concentration is a typical result. Helium concentrations (not shown) in the recovered soil gas were relatively

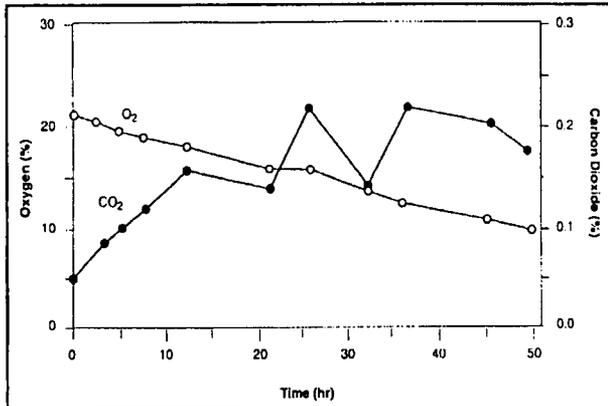


Figure 4-22 O<sub>2</sub> and CO<sub>2</sub> percentages versus time during in situ respiration test

Table 4-6  
Respiration Test Sample Data

| Time (hr) | O <sub>2</sub> (%) | CO <sub>2</sub> (%) |
|-----------|--------------------|---------------------|
| -24*      | 0.04               | 20.4                |
| 0**       | 21.0               | 0.05                |
| 2.5       | 20.4               | 0.08                |
| 5.5       | 19.7               | 0.10                |
| 8.8       | 18.7               | 0.12                |
| 13.5      | 18.0               | 0.16                |
| 22.5      | 15.4               | 0.14                |
| 27.0      | 15.2               | 0.21                |
| 32.5      | 13.9               | 0.14                |
| 37.0      | 13.0               | 0.21                |
| 46.0      | 11.3               | 0.20                |
| 50.0      | 10.6               | 0.17                |

\* Time = -24 hr indicates soil conditions prior to air injection.

\*\* Time = 0 indicates shutdown of air injection.

constant at levels close to the injected concentration. (If the helium concentrations had decreased significantly, then the validity of the

O<sub>2</sub> and CO<sub>2</sub> data would be suspect, since leakage or short-circuiting might be occurring.)

(b) Biodegradation rates were developed based on the oxygen utilization rates and the stoichiometric relationship between oxygen and a hydrocarbon representative of jet fuel, in this case assumed to be hexane (Hinchee et al. 1992). This relationship is explained in the following equation:



(c) The biodegradation rate can then be estimated using the following equation:

$$K_B = \frac{-(0.01) \times K_O \times \theta_A \times \frac{1,000 \text{ l-air}}{m^3 \text{ -air}} \times D_O \times C}{\rho_S} \quad (4-13)$$

where

$K_B$  = biodegradation rate (mg-hexane per kg-soil per day)

$K_O$  = oxygen utilization rate (percent per day)

$\theta_A$  = air-filled porosity (m<sup>3</sup>-air/m<sup>3</sup>-soil)

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$D_o$  = density of oxygen gas (mg-O<sub>2</sub>/l-air)

$C$  = stoichiometric mass ratio of hydrocarbon to oxygen

$\rho_s$  = bulk dry density of soil (kg-soil/m<sup>3</sup>-soil)

(d) Table 4-7 presents the bulk density of a variety of soil types, ranging from very permeable sands to low permeability clays. Sands will tend to have high air-filled porosities compared to very "tight" clays that may have very low air-filled porosities. Leeson and Hinchee (1995), indicate that air-filled porosity ( $\theta_A$ ) can vary widely in BV pilot tests with substantial effects on in situ respiration rate calculations. They go on to indicate that the  $\theta_A$  for some clays may be as high as 0.5 to 0.6 and the values for most sites will be within the 0.1 to 0.4 range (Leeson and Hinchee 1995). However, this discussion does not adequately account for the effects of capillary forces on the moisture content in fine-grained soils. Capillary forces prevent moisture from draining from these soils, under normal atmospheric conditions and even when substantial vacuums are applied, as during multi-phase extraction (Baker and Groher 1998). The pore spaces of fine-grained soils such as silts and clays may contain substantial amounts of water, even in soil horizons otherwise considered unsaturated (i.e., the vadose zone). Table 4-8 provides a tabulation of typical moisture saturations and air-filled porosities for a variety of soil types, all much lower than the 0.5 to 0.6 described above. The air-filled porosities presented in this table are the maximum that would be expected for these soil types. The percentage of the soil pores that are filled with water is higher in the soil closer to the capillary fringe. Thus, the closer to the water table the soil strata being tested, the lower the  $\theta_A$ . Overestimates of  $\theta_A$  will cause significant overestimates of in situ respiration rates. Obtaining field measurements of moisture content (e.g., Gardner, 1986) prior to and during in situ respiration is recommended (Baker 1999).

**Table 4-7**  
**Bulk Density of Various Soils**

| Soil Description                               | Porosity | Soil Bulk Density (kg/m <sup>3</sup> )** |
|--|----------|--|
| Uniform sand, loose                            | 0.46     | 1,430                                    |
| Uniform sand, dense                            | 0.34     | 1,750                                    |
| Mixed-grain sand, loose                        | 0.40     | 1,590                                    |
| Mixed-grain sand, dense                        | 0.30     | 1,860                                    |
| Windblown silt (loess)                         | 0.50     | 1,360                                    |
| Glacial till, very mixed-grained               | 0.20     | 2,120                                    |
| Soft glacial clay                              | 0.55     | 1,220                                    |
| Stiff glacial clay                             | 0.37     | 1,700                                    |
| Soft slightly organic clay                     | 0.66     | 930                                      |
| Soft very organic clay                         | 0.75     | 680                                      |
| Soft montmorillonitic clay (calcium bentonite) | 0.84     | 430                                      |

\*After Leeson and Hinchee, (1995), originally from Peck et al. (1962).

\*\* Dry weight

**Table 4-8**  
**Saturation ranges and Typical Air Filled Porosities for Various Soils\***

| Soil Type       | Field Capacity** Range<br>(cm <sup>3</sup> water/cm <sup>3</sup> soil) | Saturation Range***<br>(cm <sup>3</sup> water/cm <sup>3</sup> soil) | Average air filled porosity<br>( $\theta_A$ ) @ field capacity<br>(cm <sup>3</sup> air/cm <sup>3</sup> soil) |
|-----------------|--|---|--|
| Sand            | 0.13 - 0.16  | 0.36 - 0.40   | 0.24   |
| Loam Sand       | 0.15 - 0.19  | 0.36 - 0.43   | 0.22   |
| Sand Loam       | 0.17 - 0.24  | 0.37 - 0.44   | 0.20   |
| Loam            | 0.23 - 0.30  | 0.42 - 0.49   | 0.19   |
| Sandy Clay Loam | 0.21 - 0.30  | 0.44 - 0.49   | 0.21   |
| Sand Clay       | 0.28 - 0.38  | 0.49 - 0.52   | 0.18   |
| Silt Loam       | 0.24 - 0.33  | 0.40 - 0.51   | 0.17   |
| Silt            | 0.30 - 0.30  | 0.45 - 0.47   | 0.16   |
| Clay Loam       | 0.29 - 0.38  | 0.49 - 0.52   | 0.17   |
| Silt Clay Loam  | 0.33 - 0.39  | 0.50 - 0.53   | 0.16   |
| Silt Clay       | 0.39 - 0.47  | 0.53 - 0.55   | 0.11   |
| Clay            | 0.39 - 0.49  | 0.51 - 0.55   | 0.09   |

\*Estimated based on soil texture characteristics (Saxton et al. 1986)

\*\*Water content of "drained" soil

\*\*\*Volumetric water content when all pores are water filled

(e) For this example problem, the following assumptions were made regarding the parameters  $A$ ,  $D_o$ , and  $C$ :

- The soil was a poorly-sorted sand, similar to the mixed-grain loose sand in Table 4-7, which can be expected to drain well and have pore spaces mostly filled with air, not water
- Total soil porosity = 0.4, and air-filled soil porosity,  $\theta_A = 0.24$  (from Table 4-8)
- Soil bulk density = 1,590 kg soil/m<sup>3</sup>
- $D_o = 1,330$  mg/l at standard temperature and pressure
- One mole of hexane (0.086 kg) requires 9.5 moles of O<sub>2</sub> (0.304 kg) to completely oxidize it to CO<sub>2</sub> and water, for a mass ratio,  $C$ , of 1:3.5

(f) Using these assumptions and the empirical data for  $K_o$ , a biodegradation rate was found by substituting the values into Equation 4-13:

$$K_B = \frac{-10 \times \left(\frac{5\%}{\text{day}}\right) \left(\frac{0.24 \text{ m}^3 - \text{air}}{\text{m}^3 - \text{soil}}\right) \left(\frac{1,330 \text{ mg} - \text{O}_2}{I - \text{air}}\right) \left(\frac{1 \text{ mg } C_6H_{14}}{3.5 \text{ mg } O_2}\right)}{1,590 \text{ kg} - \text{soil}/\text{m}^3 - \text{soil}} = 2.9 \text{ mg hexane per kg} - \text{soil per day}$$

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#### 4-8. Field Criteria for Estimating SVE Feasibility

Peargin and Mohr (1994) reported on their use of a database of SVE pilot tests to identify common mechanical/procedural problems in monitoring vacuum distribution, and to develop field pass/fail criteria for estimation of SVE feasibility. This section reviews their methodology, results and conclusions.

*a. Vacuum distribution criteria.* To improve upon the quality of SVE pilot test data generated by their consultants, Chevron Research and Technology Company developed guidelines based on review of over 80 single well SVE pilot tests performed between 1991 and 1994 throughout the U.S. (Peargin and Mohr 1994). These guidelines include a field check of vacuum distribution observed at monitoring points, with measured vacuum normalized as a percentage of extraction well vacuum and plotted versus radial distance from the vent well (Figure 4-23a).

(1) The vacuum distribution data are compared to predicted vacuums using a two-dimensional (2D) airflow model. The diagonal line plotted on each portion of Figure 4-23 is the predicted vacuum distribution assuming: (a) airflow is at steady-state in a single layer of uniform isotropic soil, in which the horizontal hydraulic conductivity,  $K_h$  is equal to the vertical hydraulic conductivity  $K_v$  (i.e.,  $K_h/K_v = 1$ ); (b) there is radial symmetry around a single SVE well; (c) the vadose zone has an open surface with no seal to restrict downward flow of air recharging the vadose zone; (d) the vent well is screened over the lower 50 percent of the depth to groundwater (DTW); (e) the well bore radius is 3 percent of the DTW; and (f) the soil probes (monitoring points) are placed at 50 percent of the DTW.

(2) Vacuum data plotted above this predicted line are considered "passing" values, because the effects of normal anisotropy ( $K_h > K_v$ ) are expected to generate vacuum at radial distances greater than the  $K_h/K_v = 1$  prediction, and will thus lie above this predicted line. For sites where preferential airflow pathways and/or airflow short-circuiting to the surface are predominant, vacuum data are expected to fall below this predicted line.

(3) An arbitrary minimum vacuum of 0.254 cm (0.1 in.)  $H_2O$  is applied as a secondary criterion to determine SVE feasibility, because smaller vacuum values are expected to be consistent with very low gradients that yield low pore-gas velocities for most soils, and thus reflect locations beyond the zone of effective air exchange. Small vacuum values are also screened out to eliminate imprecise data due to background noise such as barometric pressure variations. [This pass/fail vacuum is NOT a "pressure of influence" design parameter, but is just a cut-off value that allows comparison of  $K_h/K_v$  with what would be predicted for sites not experiencing an undo degree of preferential flow.] Values falling within zone 1 of Figure 4-23a are thus both greater than the  $K_h/K_v = 1$  prediction and greater than the 0.254 cm  $H_2O$  minimum vacuum, and are considered "passing" values. Values falling in zone 2 are below the predicted line and are thus not considered "passing" but may potentially represent significant airflow if they fall only slightly below the predicted line. Vacuum data falling in zone 3 where soil vacuums should be highest (because of proximity to the extraction well) are a strong indication of SVE infeasibility. Finally, vacuum data in zone 4 are considered to contain no useful information about SVE feasibility because they do not meet the 0.254 cm  $H_2O$  minimum criterion. To pass the field criteria, the points in zone 4 are disregarded and less than half of the remaining points may fall within zones 2 and 3.

*b. Evaluation of data.* For illustrative purposes, data from 13 pilot tests conducted in high permeability settings are presented, with the 10 passing tests shown in Figure 4-23b, and the 3 failing tests

shown in Figure 4-23c. Similarly, data from 9 pilot tests conducted in low permeability settings are also presented, with the 2 passing tests shown in Figure 4-23d, and the 7 failing tests shown in Figure 4-23e. Peargin and Mohr (1994) also present data from 24 pilot tests conducted in mixed permeability settings, 15 of which passed and 9 failed. Mechanisms believed to contribute to failure of field criteria include short-circuiting of airflow to the surface, causing an abrupt vacuum drop adjacent to the well; well inefficiency causing an abrupt vacuum drop between gravel pack and formation across the borehole interface; airflow occurring primarily through stratigraphically controlled pathways that may not be intersected by a majority of vacuum monitoring points; and slow propagation of vacuum in low permeability soil within the time scale of the pilot test.

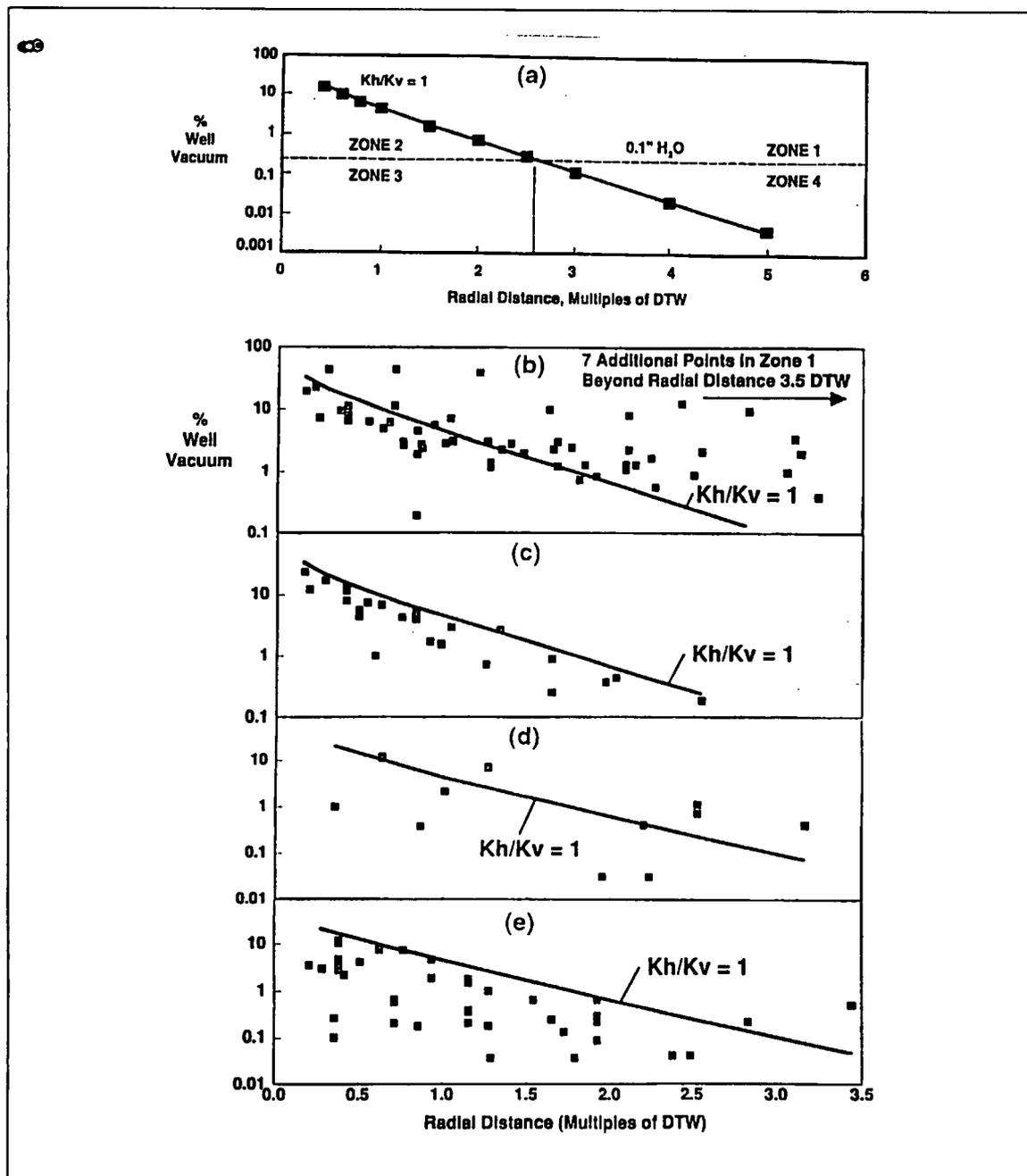


Figure 4-23 Field criteria for estimating venting feasibility, and evaluation of data from 22 pilot tests. (a) Vacuum distribution zones for pass/fail criteria; (b) High K sites passing field criteria; (c) High K sites failing field criteria; (d) Low K sites passing field criteria; (e) Low K sites failing field criteria (Peargin and Mohr 1994)

## Chapter 5 Design of Full-Scale SVE and BV Systems

### 5-1. Introduction

The main objective in designing a full-scale SVE or BV system is to provide a system that will maximize the removal of contaminants from the subsurface in the most efficient and timely manner. In order to achieve this objective, the design team must have a good understanding of the composition and characteristics of the contaminants to be removed, the location of the contaminants in relation to the water table, the characteristics of the soil in the zone of interest, the rate-limiting step in contaminant removal at the site, and the desired airflow rate and flow path to remove the contaminants from the subsurface. These data needs were addressed in Chapter 3.

### 5-2. SVE and BV Design Strategy

In order to thoroughly and properly design an effective full-scale SVE or BV system, a comprehensive design team must first be called upon. The design team should include the following:

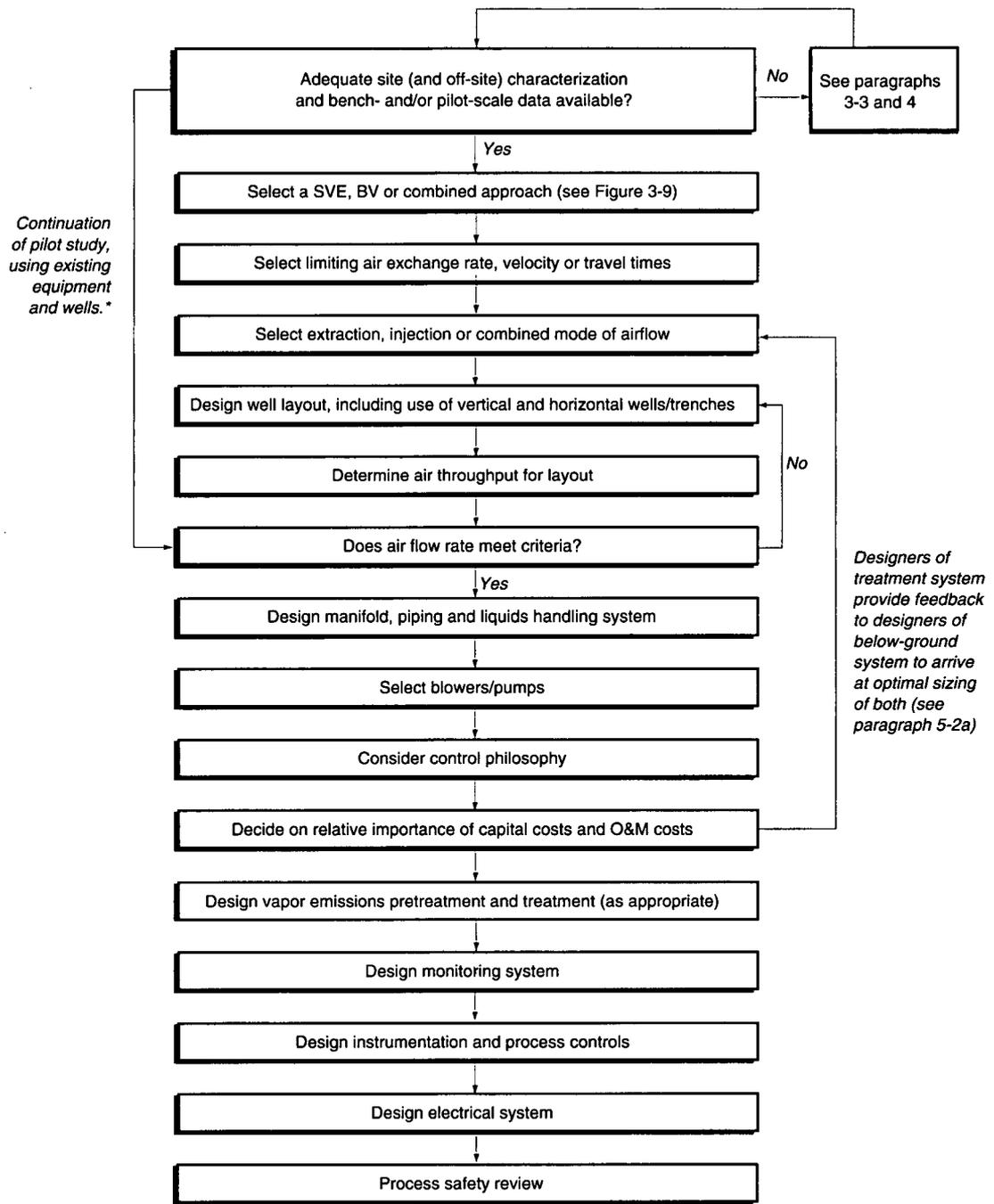
- Environmental/chemical engineer.
- Health and safety specialist.
- Mechanical engineer.
- Regulatory specialist.
- Chemist.
- Cost engineer.
- Geologist/geotechnical engineer/hydrogeologist.
- Civil/structural engineer.
- Soil scientist/soil physicist.
- Electrical engineer.

The level of involvement will vary among the disciplines; some disciplines will have a major role and will require many hours to provide input whereas other disciplines will consult on specific issues. Frequent interchange of information among disciplines is to be strongly encouraged. It is especially important that those involved with subsurface and aboveground components work together both during design and subsequent to start-up.

*a. Subsurface strategy.* A design strategy for SVE and BV systems starts with the recognition that the materials which can be removed from the subsurface with these systems are situated predominantly in the unsaturated zone and in the vicinity of the water table. The release mechanisms for moving these materials, and the rates at which they are released into the soil air and water, drive the design basis. Groundwater is not a medium that would effectively be remediated by SVE/BV alone.

(1) One of the first decisions to be made is whether to apply SVE, BV, or a combination of SVE/BV at the site. This decision will depend on the biodegradability, volatility, and concentrations of the contaminants of concern, as well as other considerations such as sensitive receptors, as discussed in paragraph 3-3.

(2) The primary design parameter is the air permeability of the soil, in both the vertical and horizontal directions, which is used in determining the "zone of effective air exchange" for each well at a given applied vacuum and airflow rate. In turn, the vacuum and flow rate can be adjusted to adequately ventilate the area of contamination and/or provide sufficient oxygen to stimulate microbial activity. The zone of effective air exchange is the volume of soil in which the air throughput is adequate to either volatilize contaminant in a reasonable target time or to provide adequate oxygen to support biodegradation of the contaminant. Conservative estimates, historical experience, and bench- and/or pilot-study results can assist the design team in estimating the zone of effective air exchange and determining the exact placement and layout of wells for the full-scale remediation system. There is often an economic tradeoff between more wells operating at lower flow rates and fewer wells operating at higher vacuums and flow rates possibly using a larger blower. Figure 5-1 illustrates the steps that are recommended to properly design a SVE or BV system.



\* For some sites, the pilot system will ultimately function as the full system.

Figure 5-1. Decision tree for SVE/BV system design

(3) The design strategy for SVE systems is to promote the release of volatile compounds from the soil, NAPL, and water film covering the unsaturated soil so that they can be carried advectively under the influence of an applied vacuum to the surface for collection and treatment. For BV systems, the air movement provides a source of oxygen to diffuse into the water film, which promotes aerobic biodegradation of the contaminants dissolved in the water phase. In the subsurface, sufficient air movement is required to match the liberation rate from the soil and the microbial needs for oxygen.

(4) In an ideal SVE design, the rate of transfer of volatile contaminants from the soil and water into the soil air would match the rate of air movement to the surface, so contaminants in the air stream would remain as concentrated as possible. In practice, maximum contaminant concentrations occur shortly after start-up of the system, then decline from this concentration with time (unless there is an ongoing release). It is usually easy to provide a vacuum extraction system that will remove the existing contaminant vapors very quickly; but over time, due to diffusion or other constraints, the rate at which volatiles are removed from other "compartments" in the subsurface becomes increasingly independent of advection and increasingly dependent on diffusion, desorption, and other transport processes (paragraph 2-3a).

(5) The expected rate of transfer of volatile contaminants from the soil and water into the soil air needs to be considered prior to initiating the design of the subsurface venting system. Figure 5-2 presents a decision tree that outlines steps involved in carrying out these considerations. It should be noted that many of these steps may already have been considered during technology screening, but they need to be looked at again at the beginning of design so that new information (e.g., from laboratory- and/or pilot-scale testing) can be incorporated into the design process. Note that the process begins by reconsidering remedial goals relative to initial contaminant concentrations and the time available for cleanup. Next, the approximate number of pore volume exchanges required to achieve remedial goals within the available time frame, in the absence of mass transfer limitations, need to be selected. (The concepts of pore volume exchange rate and its reciprocal travel time, were introduced in paragraphs 4-5f(20) to (21). The required number of pore volume exchanges, divided by the available cleanup time, equals the limiting pore volume exchange rate.) There is a lack of agreement as to the total number of pore volume exchanges required for SVE. Some experts recommend as few as 200 to 400; others 2,000 to 5,000. Experience with similar sites and contaminants, column tests, or prolonged pilot tests have been suggested as predictive tools to estimate the required number of pore volume exchanges for a given site. Unless target cleanup goals are low or initial concentrations are very high, 1,000 to 1,500 pore volumes would be a good estimate of the required air exchanges. If the air exchange rates are too high, the removal of mass will be limited by diffusion kinetics. For BV, recommended pore volume exchange rates to meet microbial oxygen demand range from  $1/4$  to  $1/2$   $d^{-1}$ . In other words, it is desirable to achieve pore-gas velocities in the treatment zone such that the maximum travel time is between 2 and 4 days from the edge of the treatment zone (where air contains high percentages of oxygen) to the extraction or injection wells. As discussed in section 5-3a(2), average pore-gas velocity is an alternate design criterion for developing an SVE/BV design. Current SVE research indicates that it is desirable to achieve pore-gas velocities throughout the treatment zone in excess of 0.001 cm/sec, or  $\sim 3$  ft/day (DiGiulio and Ravi 1999). If performance specifications are to be used, the vacuums required at specific distances from the vent wells must be consistent with pressure gradients that yield adequate travel times or velocities. In summary, with either SVE or BV, potential rate limitations need to be reconsidered at this time, either quantitatively or qualitatively (Figure 5-2). Methods of doing so are described in the following four paragraphs.

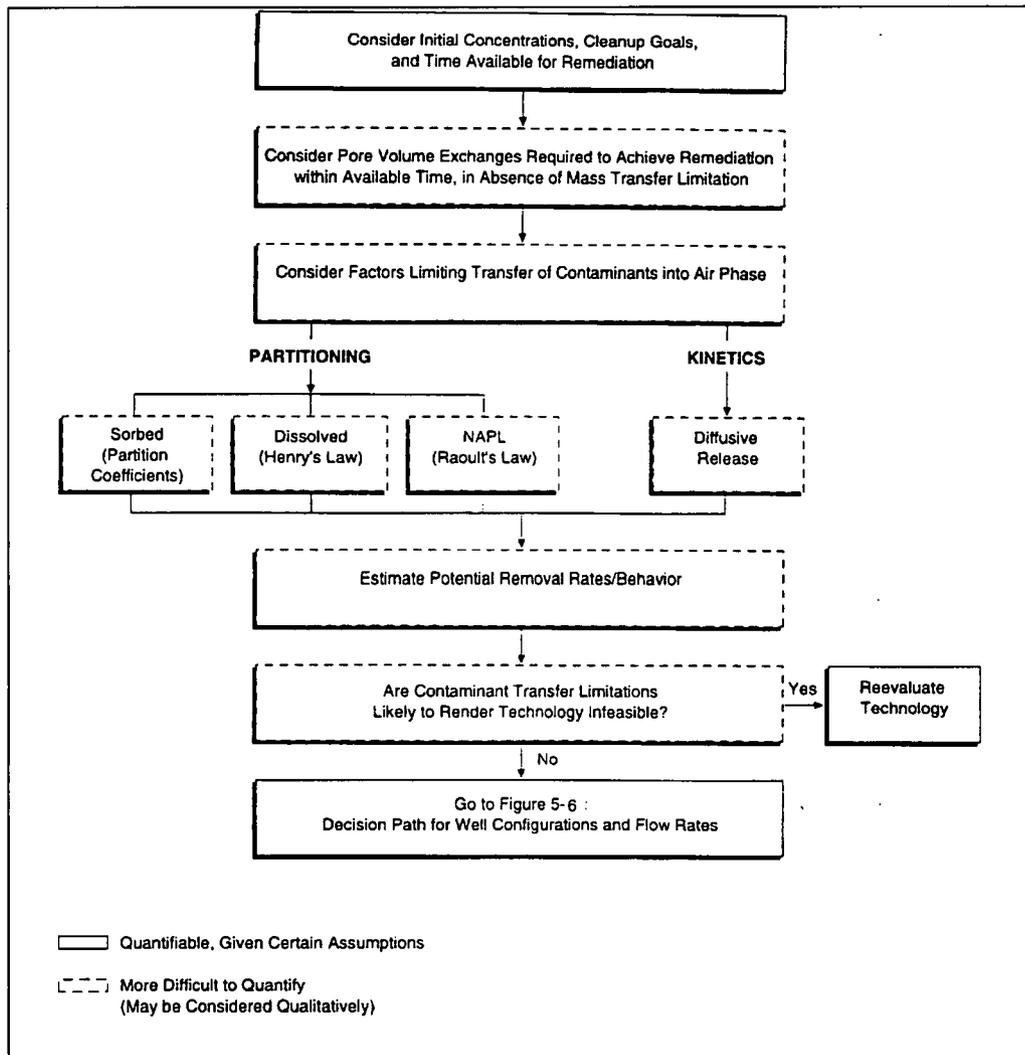


Figure 5-2. Considerations prior to well layout/airflow design.

(6) The zone of effective air exchange should correspond to the volume of soil that can be remediated within an acceptable time frame. To a certain extent, this zone can be expanded by increasing the flow rate from an individual vent. However, if the duration of remediation is too long, additional, more closely spaced wells should be operated with smaller zones of effective air exchange by decreasing the flow rate from individual vents. As the system is operated, less airflow may be required as portions of the site achieve goals and the number of operating vents may decrease. The blower selection should provide flexibility to account for these considerations. Use of a variable speed motor drive (i.e., VFD) for the vacuum blower is an excellent method of achieving the necessary flexibility.

(7) Consider injection of air during the development of a SVE strategy. Most importantly, air injection increases air throughput. Air injection can enhance air throughput without the need for higher vacuums which may cause undesirable water table upwelling. It can also limit infiltration of vapors from other sites. Air injection can be passive, dependent on atmospheric air entry into an open well based on the vacuum felt by the well screen, or active, where a blower is used to force air into the subsurface. Though rarely used, air injection can be an effective tool in SVE design.

(8) For bioventing, excessive aeration of the subsurface will not only satisfy the oxygen demand, promoting biodegradation, but more VOCs will be removed to the surface than with a slower airflow. BV systems should degrade as much contamination in the subsurface as possible to minimize the release of VOCs to the atmosphere or the need to destroy these compounds at the surface. The required volume of air per time may change as cleanup progresses due to partial remediation and reduced oxygen demand as the more easily degraded compounds are lost. Thus with BV, as with SVE, a vacuum pump or blower specification needs to consider operating requirements which may vary throughout the life of the project.

(9) Partitioning relations can be used to estimate contaminant removal rates as a function of time. Raoult's law, Henry's law, and soil vapor partitioning relations can be used to evaluate partitioning from NAPL, water, and soil, respectively. Changes in contaminant composition, and declining contaminant concentrations, must be considered when estimating future contaminant removal rates. Johnson and others (1990b) provide an evaluation of the change in gasoline composition with continued partitioning via Raoult's law. The assumption of equilibrium is often violated due to diffusion kinetics. Johnson and others (1990a) account for this limitation through the use of an "efficiency factor." The rates of diffusion can be computed based on assumed concentration gradients. If the computed diffusion rates appears to be too slow to remove mass from thick low-permeability strata, measures such as pneumatic fracturing or in-situ thermal treatment methods may be appropriate. Just such an approach has been proposed for a Marine Corps Air Station site in California (G. Kistner, EPA Region 9, personal communication 1999).

(10) Contaminant retardation should also be considered when estimating contaminant removal rates. As air travels toward an extraction vent, contaminants will sorb and desorb, and volatilize and dissolve, in response to changing soil conditions and contaminant concentrations. These processes commonly result in contaminant removal rates being far lower than would be the case were there no limitations to the release and movement of the contaminants with the advective airflow. The term "retardation" has been used to describe delayed contaminant removal resulting from sorption/desorption processes. However, the same concept applies to partitioning from dissolved and NAPL phases.

(11) Removal rates can be calculated using coupled airflow and contaminant partitioning models, or they can be estimated based on pilot tests and column studies. Although airflow models usually provide reasonable estimates of vapor flow rates and travel times, contaminant partitioning is more difficult to simulate. This results from the numerous interrelated processes involved, and the physical and chemical

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properties of heterogeneous soil. With caution, experienced modelers may obtain estimated contaminant removal rates via modeling. Alternatively, pilot studies or column tests can be used. The pilot tests can provide additional data against which models can be calibrated. The total time for remediation can be calculated by integrating the (often highly non-linear) estimated and extrapolated contaminant removal rate over time and comparing to estimates of the mass present.

(12) Observed mass removal rates can be calculated from vapor concentrations and flow rates using the equation presented in Table 7-4.

(13) In cases where a combined SVE/BV approach will be applied, the implications of the changeover from SVE to BV should be considered. Design considerations include:

- The likelihood that reduced airflow rates will be needed during BV.
- A dramatically changed monitoring program, including measurement of soil gas and offgas oxygen and carbon dioxide concentrations, pH, moisture, nutrient concentrations, and temperature.
- The possible need for additional wells due to the fact that with lower airflow rates, the zone of effective air exchange will be smaller. To some extent, this may be compensated for since BV often requires lower pore volume exchange rates and lower pore-gas velocities than SVE. Consequently, the definition of an acceptable vent spacing may change over the life of a project.

### 5-3. Well Locations

The number and locations of extraction and/or injection wells required to move air in the desired flow regime is highly site-specific and depends on many factors such as extent and depth of the contamination, physical and chemical properties of the contaminants, soil characteristics, and most important, air permeability.

*a. Well layout.* The primary goal of an SVE or BV system is to cause air transfer within the contaminated zone. For SVE systems, the goal is to provide air throughput at a rate that allows efficient transfer of contaminants but is still fast enough to remediate the soil within a desired time frame. For BV systems, the goal is to provide adequate air to prevent oxygen deficiency from being a limiting factor in bioremediation. The well layout must allow adequate air transfer within the target zone.

(1) Inadequacy of Radius of Influence (ROI) as Design Basis. In the past, designers have often used a "radius of influence" approach to choosing well spacing. The radius of influence (paragraph 4-5f), more accurately termed "radius of vacuum influence", has typically been defined based on some small but measurable vacuum (or pressure) level due to some extraction (or injection) rate. It is assumed that since vacuum is detectable, then air is moving and the soil is being treated. Well spacing would then be chosen on some factor, say 1.5 times the estimated radius of pressure influence at the projected flow rate. Unfortunately, this fails to consider the actual air throughput at points intermediate between vents. There may be minimal flow in these areas.

(a) Problems associated with ROI-based venting designs have been discussed in refereed literature (Johnson and Ettinger 1994; Nyer et al. 1994), yet, ROI testing continues to be used for venting design at

many sites. Practitioners who use ROI testing to design soil venting systems assume that observation of subsurface vacuum ensures sufficient airflow in contaminated soils for timely remediation via organic compound volatilization and/or biodegradation. As Johnson and Ettinger (1994) point out, however, measurement of vacuum says very little about pore-gas velocities that prevail within the subsurface. Pore-gas velocity is proportional to the product of the pressure gradient (i.e., pressure difference over a given distance within the soil) and the air permeability within that soil. **Since air permeability,  $k_a$ , can often vary 100 to 10,000-fold from one soil type to another, it is the  $k_a$  value within the soil, rather than the pressure gradient, that usually governs the pore-gas velocity.** For example, a soil consisting of two layers having contrasting air permeabilities that are both subjected to the same applied vacuum along a lateral boundary will, upon attainment of a steady state, exhibit exactly the same pressure gradient in both the high and low permeability layers. Meanwhile, however, the pore-gas velocity can be orders of magnitude greater within the high permeability layer than within the adjacent low permeability layer (Figure 5-3).

(b) Consequently, basing a venting design on measurement of vacuums alone, at best, only ensures capture and containment of contaminant vapors. (In other words, observation of a measurable vacuum does indicate that there is a pressure gradient in the direction of the vacuum well, and therefore that there may be some movement in that direction, not how fast air will flow toward that well.) Even containment comes into question when the magnitude of applied vacuum in soil is so small as to be comparable to pressure differentials caused by natural variation in barometric pressure and/or fluctuation of the water table. Diurnal barometric pressure changes in soil can be on the order of a few mbar (Massmann and Farrier, 1992), whereas 0.1 inch water vacuum (the value often adopted by ROI practitioners as indicative of significant vacuum) is equivalent to only 0.25 mbar. Thus natural pressure gradients can overwhelm the smaller pressure gradients exerted at a distance from venting wells.

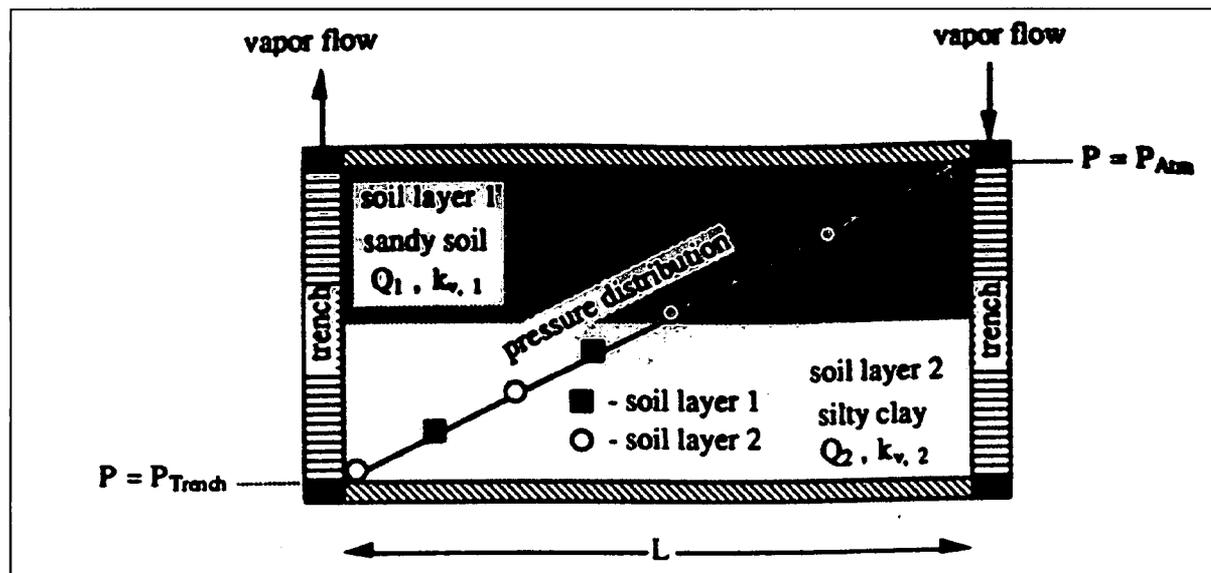


Figure 5-3. Effect of Contrasting Air Permeabilities on Pore-Gas Velocity. Figure depicts steady-state pressure distribution for 1-D flow between parallel trenches. Trenches intersect two soil strata with contrasting permeabilities (one sand and the other silty clay). Although the pressure distributions are the same in the two strata, most of the airflow will occur through the sand (Johnson and Ettinger, 1994).

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(2) Pore-Gas Velocity or Travel Times as a Preferred Design Basis. A more relevant approach to well layout is to try to achieve a pore velocity that exceeds some minimum rate, everywhere within the contaminated zone. This translates to a rate of air exchange (pore volume per time) that will lead to adequate cleanup in an allotted time. Analyses of air velocities and travel times to the extraction wells at various flow rates are thus required to verify adequate spacing (Shan, Falta, and Javandel 1992; Falta, Pruess, and Chestnut 1993). Required travel times can be estimated by dividing the time frame for remediation by the number of pore volumes required to remove a significant percentage of the contaminants. The pore volume exchanges must consider the flow paths along streamlines. In most cases where the site surface is not carefully sealed, the assumption that removal of air occurs via purely two-dimensional (horizontal) radial flow is inappropriate. Streamlines bound "streamtubes" or funnel-shaped volumes (narrowing toward the extraction vent) that conduct a given amount of air from a source, such as the atmosphere or an injection vent, to the extraction vent. The travel time through a streamtube is determined by dividing the air-filled pore volume in the tube by the flow rate of air through the tube. Streamtubes that have shorter paths from the surface or clean soil to the extraction vent will have shorter travel times than tubes that originate farther from the vent. The travel times for the tubes passing through the contaminated zone must be less than some value and the velocities at all points in the tube (within the contaminated volume or target cleanup area) must be above some threshold to achieve adequate air throughput. The product of the pressure gradient across that soil and the air permeability within it governs the pore-gas velocity within a given volume of the soil. Therefore, estimation of how pore-gas velocities will vary within the subsurface requires estimation, in turn, of both pressure gradient and air permeability within the zone in question. Computer models can be used for this analysis of velocities and travel times. Additional tools based on analytical equations describing air flow in porous media are provided below.

(a) Once a pore-gas velocity field is estimated, however, how does one know what minimum pore-gas velocity to specify as the minimum that must be attained within the contaminated domain in order for venting to be effective? Pore-gas velocities must be low enough to allow adequate time for diffusion from regions not receiving direct airflow, but high enough to avoid excessive build-up of vapors and hence excessive remediation time. Ideally, site-specific laboratory column and field studies would be conducted to determine this minimum value. Acceptable laboratory and field-scale methodologies for this determination, however, are currently unavailable. In the absence of site-specific information, results of published research can be used to estimate a minimum design pore-gas velocity or specific discharge value.

(b) A number of laboratory-scale investigations indicate that pore-gas velocities at which rate-limited vapor transport is observed are much higher for NAPL contaminated soils than non-NAPL contaminated soils. Thus, when selecting a minimum pore-gas velocity for venting design, one should distinguish whether or not NAPL is present in soils. However, even if soils are contaminated by NAPL, it may be unwise to base selection of a design pore-gas velocity totally on mass transport in NAPL contaminated soils, since time spent on venting application after eventual removal or evaporation of NAPL can be substantial.

(c) Virtually all research on selection of pore-gas velocities for venting remediation has been conducted in controlled sand tanks and laboratory columns where field-scale heterogeneity is not a factor. Thus, optimal pore-gas velocities in the field are likely to be very site-specific and somewhat smaller than indicated by controlled sand tank and laboratory column studies.

(d) The characteristic length of contamination used in equations developed to estimate design pore-gas velocities is not constant but decreases in time due to NAPL and sorbed mass removal, thereby reducing calculated optimal pore-gas velocities.

(e) The cost of well installation versus venting operation (e.g., electricity, vapor treatment) must be considered since achievement of a minimum target pore-gas velocity in contaminated soils is largely determined by balancing applied flow and spacing of venting wells. An increase in the number of venting wells results in a decrease in applied flow to achieve similar pore-gas velocities in soils. Thus, operating costs associated with blower operation and vapor treatment can be reduced by increasing construction costs associated with well drilling.

(f) In consideration of these factors, it is apparent that selection of a minimum pore-gas velocity is not a straightforward process but involves some degree of engineering judgement. Experimental sand tank and column studies suggest that pore-gas velocities in excess of 0.25 cm/s (Wilkins et al., 1995) must be present in NAPL contaminated soil for deviation from local equilibrium, while studies by Armstrong et al. (1994), Gierke et al. (1992), and Ng and Mei (1996) suggest an optimal pore-gas velocity near 0.01 cm/s for non-NAPL contaminated soils. Since the longest portion of venting operation may be associated with mass removal after evaporation of NAPL and specification of a design pore-gas velocity of 0.01 cm/s or greater will generally result in unacceptably close well spacing for a variety of site designs, **it is currently recommended that a minimum pore-gas velocity between 0.01 and 0.001 cm/s (DiGiulio and Ravi 1999), (or ~ 3 to 30 ft/day) be used for design purposes.** Cho and DiGiulio (1992) provide an example of pore-gas velocity calculations. Public domain computer codes developed by the USGS, AIR2D (Joss and Baehr, 1997) and AIR3D (Joss and Baehr, 1995) provide specific discharge calculations in axi-symmetric and three-dimensional cartesian coordinates, respectively.

(3) *Air Injection for Soil Vapor Extraction.* Air injection offers benefits in operation such as reduction of "dead zones", minimization of upwelling, increasing pressure gradients, and creating a barrier to air flow toward sensitive locations, as discussed in the following paragraphs.

(a) At sites requiring multiple wells, areas of little or no airflow are established near the intersections of the effects of the nearby wells. This can be overcome either through operation of nearby wells at varying flow rates to move the stagnation point over time or by the use of air injection wells (Figures 5-4, 5-5, and 5-6). Passive air injection wells allow air entry directly from the atmosphere into the subsurface and can significantly alter air flow, increasing flow in stagnation areas. However, since the air intake at a passive injection well is a function of the vacuum in the subsurface at the passive injection well screen and since the vacuums at the stagnation areas are often small, the actual air entry is often minor. Active air injection can be much more effective at increasing air throughput in these areas, possibly resulting in expedited remediation since these areas are often the last to clean up without air injection. Computer models can be used to project the effect of passive or active air injection wells.

(b) At sites where the contaminant mass to be removed is located near the water table, the exclusive use of vapor extraction results in maximum upwelling of the water table and capillary fringe due to the applied vacuum. This would likely reduce the effectiveness of treatment near the extraction well. The coupled use of air injection and air extraction reduces the applied vacuum "felt" by the water table for the same amount of air flow through the soils. Furthermore, the injected air can be focused in the vicinity of the water table, reducing the effort spent in moving air through relatively clean soil higher in the vadose zone. This increases effectiveness for the operation cost. Although paired extraction and injection requires additional blower(s) or blower capacity, the reduction, due to the smaller required vacuum, in the sizing of the blower(s) and the possible increase in well spacing will likely reduce overall capital costs and operational costs. In other cases where focused airflow in a specific horizon is required, the use of active air injection can also benefit the project. Computer modeling or the analytical tools described below can be

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used to determine the impact of air injection. The addition of clean air to the subsurface, if not properly considered, may also dilute vapor phase contaminant concentrations, thereby increasing offgas treatment costs.

(c) Passive inlet 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 SVE/BV to proceed at one of the properties without inducing migration of contaminants from the other property, but the inlet wells would probably need to be quite closely spaced to create an effective boundary condition.

(d) As mentioned in Chapter 3, passive venting as the sole air addition and/or removal mechanism can be used if there is adequate lag in response between the subsurface and the atmosphere. Evaluation of the pressure lag, air removal (or injection for BV) rates, and air exchange in the surrounding subsurface is required for design of a passive system.

(e) Steam can be injected instead of air to enhance the removal of low volatility contaminants or to enhance diffusion, as discussed in more detail in Chapter 3.

*b. Extraction well screen placement.*

(1) 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 only be screened within the zone that has been impacted.

(2) 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 from the water table to prevent upwelling 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 air flow paths and, therefore, the zone of effective air exchange of a given extraction well (Shan, Falta, and Javandel 1992). It is strongly suggested that flow models such as AIR2D, AIR3D, or MODFLOW (with appropriate modifications) be used to optimize screen depths. These and other SVE/BV models are described in Appendix C.

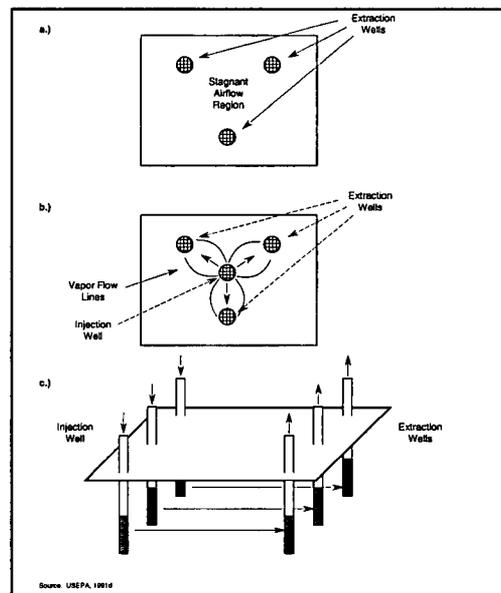


Figure 5-4. Example venting well configurations.

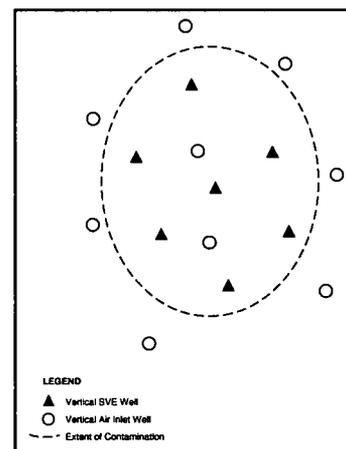


Figure 5-5. Vertical extraction/inlet well layout scheme (asymmetric layout reflects anisotropic conditions at site).

(3) In areas where the water table is shallow (i.e., less than 3 meters below ground surface), horizontal SVE/BV wells or trenches should generally be employed. Horizontal SVE/BV wells minimize the upwelling of groundwater and in such cases extract air from the unsaturated zone more efficiently.

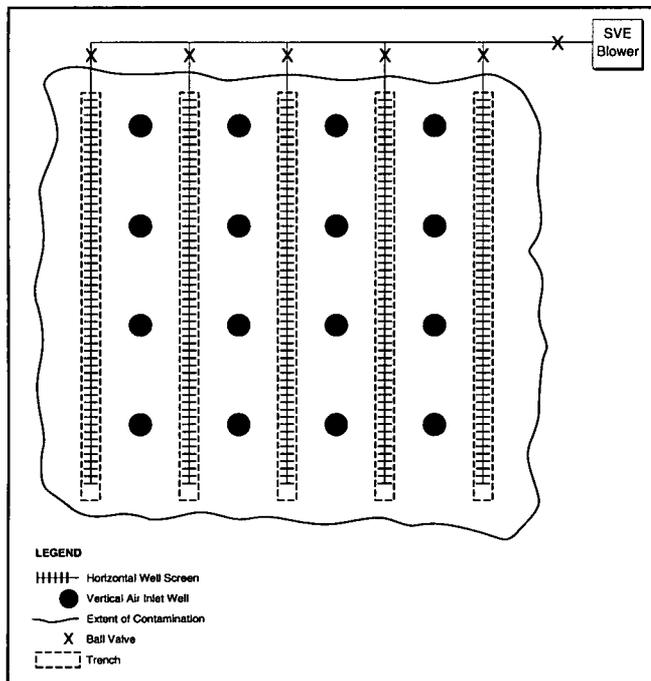


Figure 5-6. Plan view of typical horizontal extraction/vertical inlet well scheme.

*c. Passive/active injection well placement*

(1) Injection wells should be placed so that contamination is directed toward the extraction wells and not driven into uncontaminated areas or toward possible exposure points. 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. Passive/active injection wells are similar in construction to extraction wells (refer to paragraph 5-4), and the screened intervals are chosen to focus airflow into the appropriate zone to enhance contaminant recovery. Steam injection wells are typically constructed of steel.

*d. Decision path for selecting well configurations and flow rates*

(1) A decision path for selecting well configurations and flow rates is shown on Figure 5-7. The decision path focuses on single vs. multiwell systems comprised of up to four wells. The multiwell systems consist of a central extraction well surrounded by one, two, or three injection wells. SVE subsurface airflow velocity modeling or streamtube calculations are used to determine the required extraction rate and well configuration to achieve a desired air exchange rate. For sites with impermeable surface covers, the total injection rate is assumed to be equal to total extraction rate. This pumping strategy makes maximum use of the injection wells without causing offsite migration of contaminated vapors. For sites without impermeable surface covers, the extraction rate must exceed the total injection rate, since some of the extracted air represents breakthrough from the atmosphere.

(2) The multiwell systems evaluated represent typical well configurations for SVE and BV applications. These configurations represent somewhat idealized geometries that are unlikely to be reproduced exactly during field installation. However, the well configurations shown can be used as a guide for SVE/BV design. Well spacings and flow rates for other well and trench configurations can be determined using a similar approach.

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(3) The primary considerations for selection of well configurations and flow rates are a) the geometry of the contaminated zone, b) the air permeability and horizontal to vertical permeability ratio, and c) the desired air exchange rate. Using these data, well configurations and flow rates can be systematically evaluated using the nested decision loops shown in Figure 5-7. Each well configuration in the outer "Well Configuration" loop is evaluated against offgas treatment limitations, blower horsepower, and water table upwelling limitations in the inner "Acceptance Criteria" loop. The following paragraphs explain the actions required at each step of the decision path.

(4) In conjunction with the flow rate that can be achieved by individual wells, the size of the contaminated zone exerts the predominant control on the number of wells that will be required. Similarly, the geometry of the contaminated zone controls the spatial configuration and optimum screened intervals of the wells.

(5) Either air permeability measurements or pilot test data are required to evaluate blower horsepower and water table upwelling, whereas anisotropy measurements (the ratio of horizontal to vertical permeability) are required to evaluate well configurations. Recommended methods for analysis of air permeability and anisotropy are presented in Appendix D.

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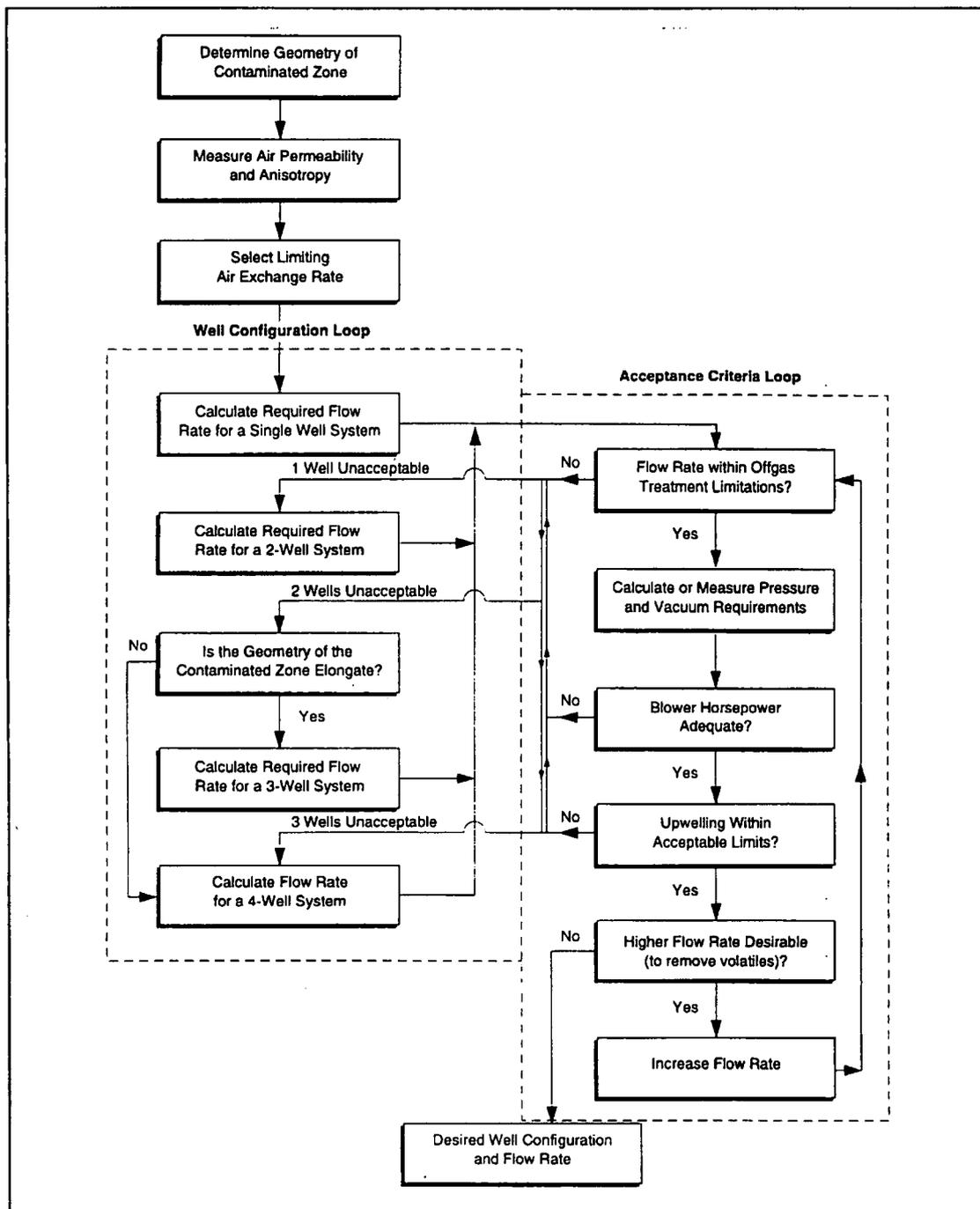


Figure 5-7. Decision path for well configurations and flow rates.

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For this development, flow rate calculations are based on a minimum air exchange rate within the contaminated zone. This approach is probably more valid for BV applications, where air exchange rates are low enough that sorption and diffusion limitations are less important. If the minimum air exchange rate exceeds the rate of contaminant release from diffusion- or sorption-limited zones (as for some SVE applications), this approach is not valid. Pilot tests or column studies may be useful for identifying the minimum air exchange rate.

(6) Because single well systems generally involve the lowest installation cost, these systems form the first tier of the well configuration loop (Figure 5-7). For sites **with impermeable surface covers**, the required flow rate for a single well system can be calculated via:

$$Q_v^* = \frac{\pi r^2 b n_a}{t_{ex}} \quad (5-1)$$

where

$Q_v^*$  = volumetric flow rate at atmospheric pressure [ $L^3/T$ ]

$r$  = radius of the treatment zone [L]

$b$  = vadose zone thickness [L]

$n_a$  = air-filled porosity of the soil [ $L^3/L^3$ ]

$t_{ex}$  = the time required for one pore volume exchange [T]

Equation 5-1 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(7) For sites without impermeable surface covers, flow rate calculations require determination of the travel time from the limits of contamination to the extraction well. If the maximum extent of contamination occurs near the ground surface, dimensionless travel times provided by Shan, Falta, and Javendal (1992) can be used to determine the required flow rate. Using the definition of dimensionless travel time provided by them, the required flow rate for a single well system is:

$$Q_v^* = \frac{2 \pi b^2 n_a A (L - l) \tau}{t_{ex}} \quad (5-2)$$

where:

$Q_v^*$  = volumetric flow rate at atmospheric pressure [ $L^3/T$ ]

$A$  = ratio of horizontal to vertical permeability

$l$  = depth to the top of the well screen [L]

$L$  = depth to the bottom of the well screen [L]

$\tau$  = dimensionless travel time from Shan et al. (1992)

This analysis is based on the travel time from the ground surface to the extraction well, as provided by Shan, Falta, and Javendal. The streamline originating near the lateral limits of the contamination is chosen as the critical (maximum travel time) path. The flow necessary to achieve an acceptable travel time along this path is chosen for design. If the maximum extent of contamination occurs near the water table, then dimensionless travel times obtained from Figure 5-8 may be used in Equation 5-2. It should be noted, however, that the dimensionless travel times shown in Figure 5-8 assume that there is no reduction in flow velocity due to increased water saturation near the water table.

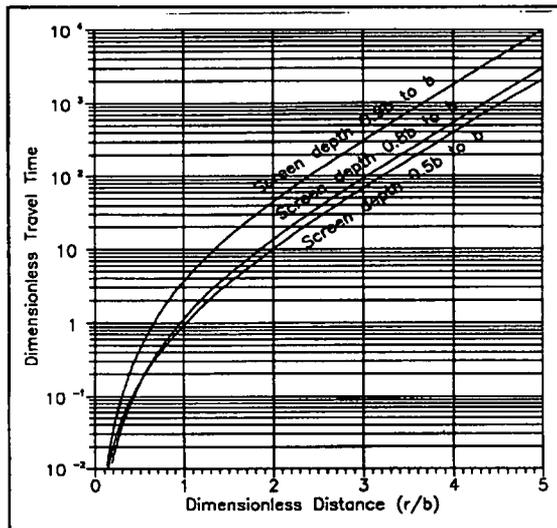


Figure 5-8. Dimensionless travel times at the water table for wells screened within the lower half, fifth, and tenth of the vadose zone (Brailey 1995, unpublished data).

of safety" to account for stagnation zones, or numerical modeling should be applied to determine optimum well placement. Again, the goal is to achieve a minimum velocity or some maximum travel time along the longest air streamline.

(10) If the required flow rate for a single well system exceeds the acceptance criteria shown in Figure 5-7, the decision path aborts to evaluation of two-well systems (paired extraction and injection wells). For sites with impermeable surface covers, flow from an injection well to an extraction well is primarily horizontal, and can be represented in plan view as shown in Figure 5-9. Note that in the streamtube plots that follow, each of the streamtubes transmits an equal fraction of the total airflow represented within the drawing.

(11) The flow geometry shown in Figure 5-9 applies where the extraction rate equals the injection rate. As shown in Figure 5-9, about 50 percent of the flow occurs inside a circle containing both wells. Flow outside the circle is relatively slow (indicated by the width of the streamtubes), and has potential for offsite migration of contaminants. As a result, the wells should be placed at either end of the maximum horizontal extent of the treatment zone. In this manner, the streamtubes with the highest flow velocity lie directly between the two wells, and there is limited potential for offsite migration of contaminated vapors.

(8) To evaluate the adequacy of a single well system, the flow rate obtained from Equation 5-1 or 5-2 should be compared against the acceptance criteria shown in Figure 5-7. Since the vacuum necessary to develop the design flow rate may exceed blower horsepower or water table upwelling limitations, vacuum requirements should be measured or calculated using the appropriate flow equations. Well inefficiencies and friction losses through piping and equipment must also be considered. Alternatively, pilot test data can be used to estimate vacuum requirements.

(9) The following paragraphs discuss the design strategy for multi-well system that include active air injection. In many cases, the use of air injection adds significant benefit to the remediation by increasing air throughput at lower vacuums. If, however, air extraction is the only alternative for a larger system, then either the extrapolation of the results of the single well analysis, with some "factor

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(12) Note that the two-well geometry is somewhat inefficient, because about 50 percent of the flow occurs outside the treatment zone. As a result, this geometry is appropriate where there is limited resistance to flow, and the system capacity is adequate for ventilation of soils both within and outside the treatment zone.

(13) The required flow rate for a two-well system can be obtained by setting the air exchange rate in the outermost streamtube equal to the design criterion. The outermost streamtube of the treatment zone corresponds to streamtube No. 6 in Figure 5-9. Noting that streamtube No. 6 carries 1/20 of the design flow rate, the travel time from the injection well to the extraction well is:

$$t = \frac{V_{\#6}}{\frac{1}{20} Q_v^*} = \frac{0.133 L^2 b n_a}{\frac{1}{20} Q_v^*} = \frac{2.66 L^2 b n_a}{Q_v^*} \tag{5-3}$$

where

$V_{\#6}$  = volume of streamtube No. 6 [L<sup>3</sup>]

$Q_v^*$  = volumetric flow rate at atmospheric pressure [L<sup>3</sup>/T]

$L$  = distance between the two wells [L]

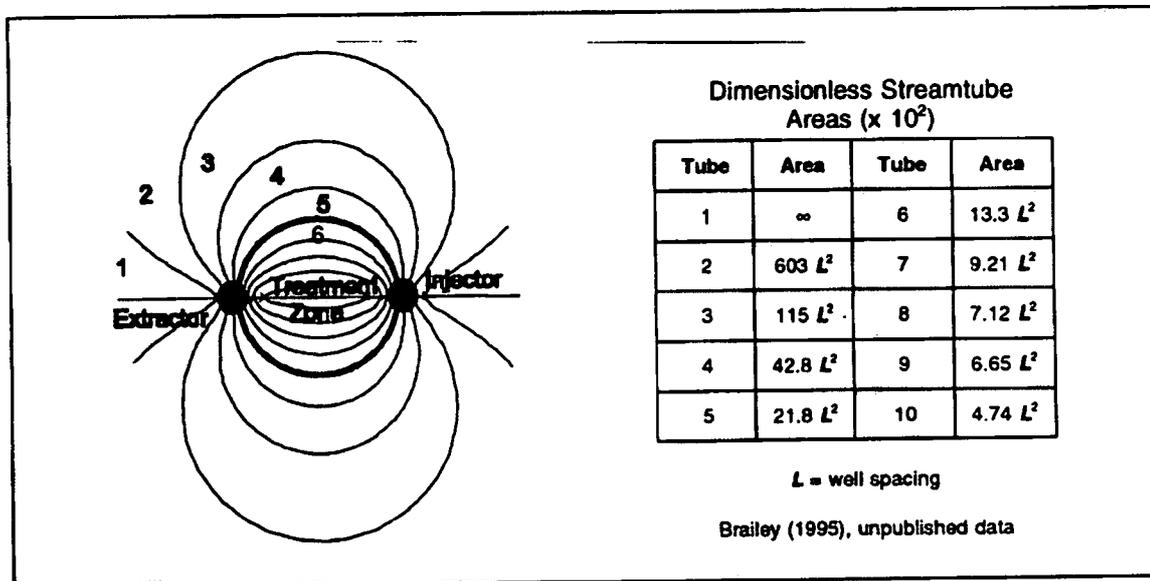


Figure 5-9. Plan view of streamtubes for a two-well system

To determine the required flow rate, use Equation 5-4 setting the time for one pore volume exchange ( $t_{ex}$ ) equal to the design criterion:

$$Q = \frac{2.66 L^2 b n_a}{t_{ex}} \tag{5-4}$$

Equation 5-4 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(14) For sites without impermeable surface covers, the three-dimensional flow geometry makes plan view representation difficult. Close to the water table, however, the flow geometry is similar to that shown in Figure 5-10. In cross section, the flow geometry for wells screened within the bottom third of the vadose zone, with a well spacing equal to  $1.6bA^{1/2}$ , is shown in Figure 5-10. This well spacing represents the maximum spacing that will not cause substantial breakthrough of atmospheric air between the extraction well and the injection well.

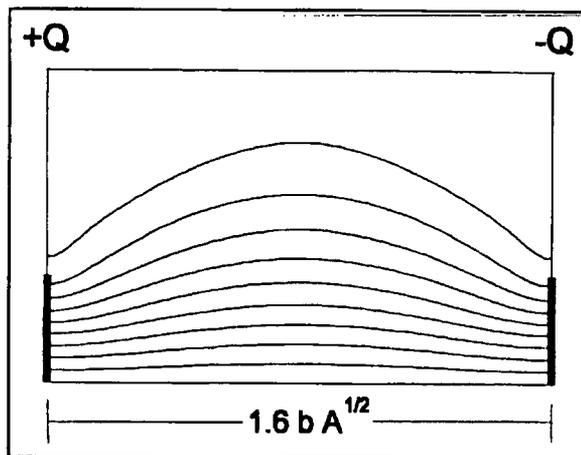


Figure 5-10. Profile of streamtubes for a two-well system.

evaluated. If the contaminated zone is elongated in plan view, then a three-well system should be considered. If the contaminated zone is roughly symmetric in plan view, then a four-well configuration is more appropriate.

(17) As shown by Figure 5-11, three-well systems are best suited for elongated treatment zones. For sites with impermeable surface covers, flow from an injection well to an extraction well is primarily horizontal, and can be represented in plan view as shown in Figure 5-11.

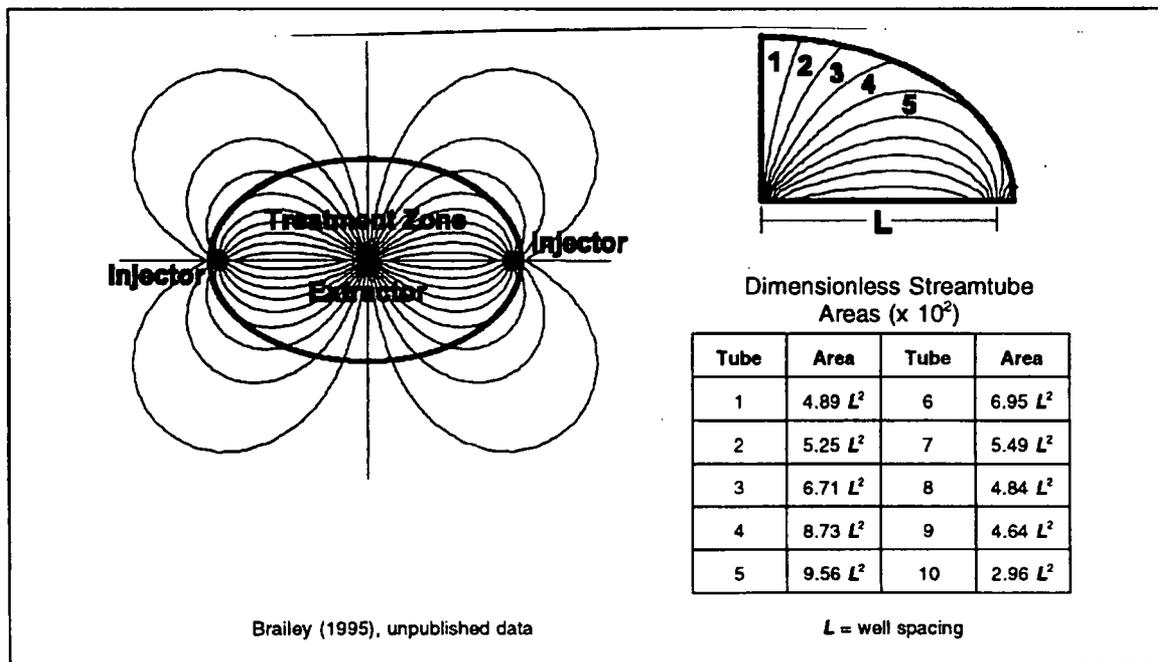
(18) The flow geometry shown in Figure 5-11 applies where the total injection rate equals the total extraction rate. As a result, the flow rate into each injector is one-half of the flow rate from the central extractor. As shown in Figure 5-11, about 60 percent of the flow from injection to extraction wells falls within an ellipse, where the width-to-length ratio of the ellipse is about 0.65. Flow outside the ellipse is relatively slow, and has potential to cause offsite migration of contaminants. As a result, two wells should be placed at either end of the treatment zone, and a third well should be placed along the centerline midway between the outer wells. In this manner, the streamtubes with the highest flow velocity lie directly between the two wells, and there is limited potential for offsite migration of contaminated vapors.

For wells screened within the bottom third of the vadose zone, the required flow rate can be determined by first verifying that  $L \leq 1.6bA^{1/2}$ . Then, Equation 5-4 can be used to calculate the required flow rate.

(15) The amount of atmospheric breakthrough can be controlled by changing the well spacing, screened interval, and flow rate. Although smaller well spacings will result in less atmospheric breakthrough, streamtube modeling is required to evaluate well spacings and screened intervals other than those shown in Figure 5-10.

(16) If an adequate air exchange rate cannot be accomplished with a two-well system, then three- or four-well configurations may be

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**Figure 5-11. Plan view of streamtubes for a three-well system.**

(19) The required flow rate for a three-well system can be obtained by setting the air exchange rate in the outermost streamtube equal to the design criterion. The outermost streamtube of the treatment zone corresponds to streamtube No. 5 in Figure 5-11. Noting that streamtube No. 5 carries 1/40 of the design flow rate, the travel time from the injection wells to the extraction well is:

$$t = \frac{V_{\#5}}{\frac{1}{40} Q_v^*} = \frac{0.0956 L^2 b n_a}{\frac{1}{40} Q_v^*} = \frac{3.82 L^2 b n_a}{Q_v^*} \quad (5-5)$$

where

$$V_{\#5} = \text{volume of streamtube No. 5 [L}^3\text{]}$$

To determine the required flow rate, use Equation 5-6 setting the time for one pore volume exchange ( $t_{ex}$ ) equal to the design criterion:

$$Q = \frac{3.82 L^2 b n_a}{t_{ex}} \quad (5-6)$$

Equation 5-6 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(20) For sites without impermeable surface covers, the three-dimensional flow geometry makes plan view representation difficult. Close to the water table, however, the flow geometry is similar to that shown in Figure 5-12. In cross section, the flow geometry for wells screened within the bottom third of the vadose

zone, with a well spacing of  $1.6bA^{1/2}$ , is shown in Figure 5-12. This well spacing results in only minor breakthrough of atmospheric air along the longitudinal axis of the treatment zone (A-A'), but there is substantial breakthrough in the transverse direction (B-B'). For wells screened within the bottom third of the vadose zone with a well spacing of  $1.6bA^{1/2}$ , the extraction rate calculated using Equation 5-6 should be increased by about 50 percent to account for the breakthrough shown on B-B'. The injection rate, however, should remain the same.

(21) The amount of atmospheric breakthrough can be controlled by changing the well spacing, screened interval, and flow rate. Although smaller well spacings will result in less atmospheric breakthrough, streamtube modeling is required to evaluate well spacings other than those shown in Figure 5-12.

(22) As shown in Figure 5-13, four-well systems are best suited for treatment zones that are symmetric in plan view. For sites with an impermeable surface cover, flow from injection wells to extraction wells is primarily horizontal, and can be represented in plan view as shown in Figure 5-13.

(23) The flow geometry shown in Figure 5-13 applies where the total injection rate equals the total extraction rate. As a result, the flow rate into each injector is one-third of the flow rate from the central extractor. Placement of injection wells at the limit of the treatment zone avoids relatively low flow rates near the perimeter of the flow field (indicated by the width of the streamtubes). This well placement also limits the potential for offsite migration of contaminated vapors.

(24) The required flow rate for a four-well system can be obtained by setting the air exchange rate in the outermost streamtube equal to the design criterion. The outermost streamtube of the treatment zone corresponds to streamtube No. 1 in Figure 5-13. Noting that streamtube No. 1 carries 1/60 of the design flow rate, the travel time from the injection wells to the extraction well is:

$$t = \frac{V_{\#1}}{\frac{1}{60} Q_v^*} = \frac{0.0754 L^2 b n_a}{\frac{1}{60} Q_v^*} = \frac{4.52 L^2 b n_a}{Q_v^*} \quad (5-7)$$

where

$$V_{\#1} = \text{volume of streamtube No. 1 [L}^3\text{]}$$

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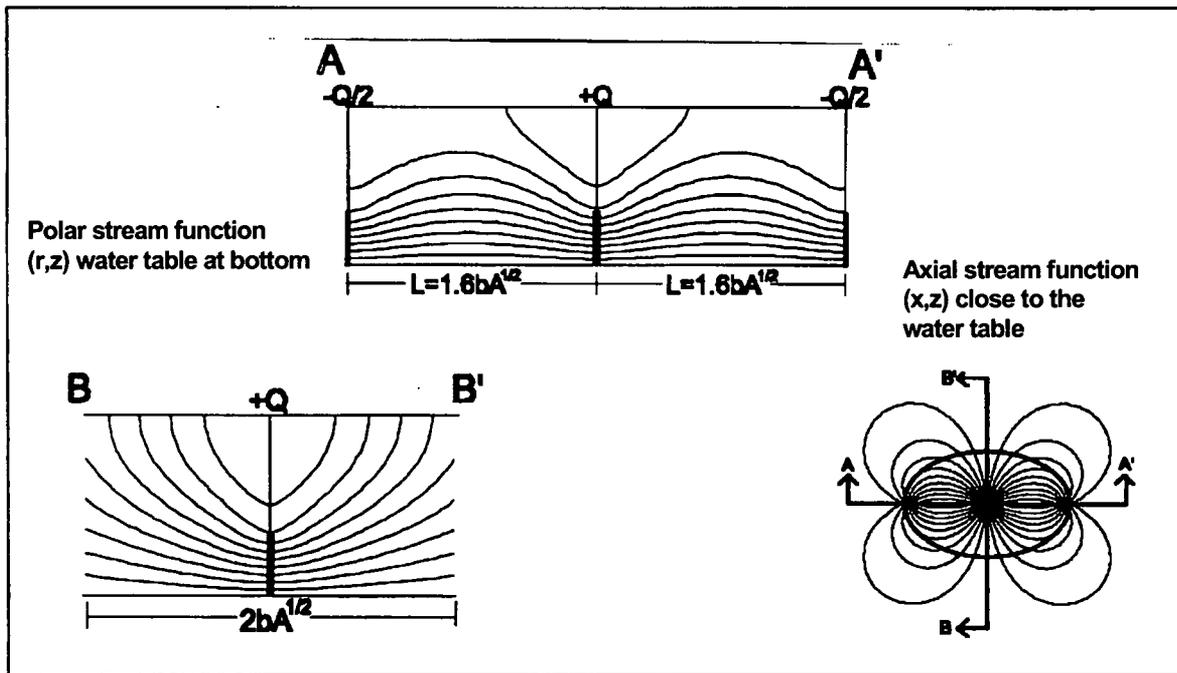


Figure 5-12. Streamtube profiles for a three-well system.

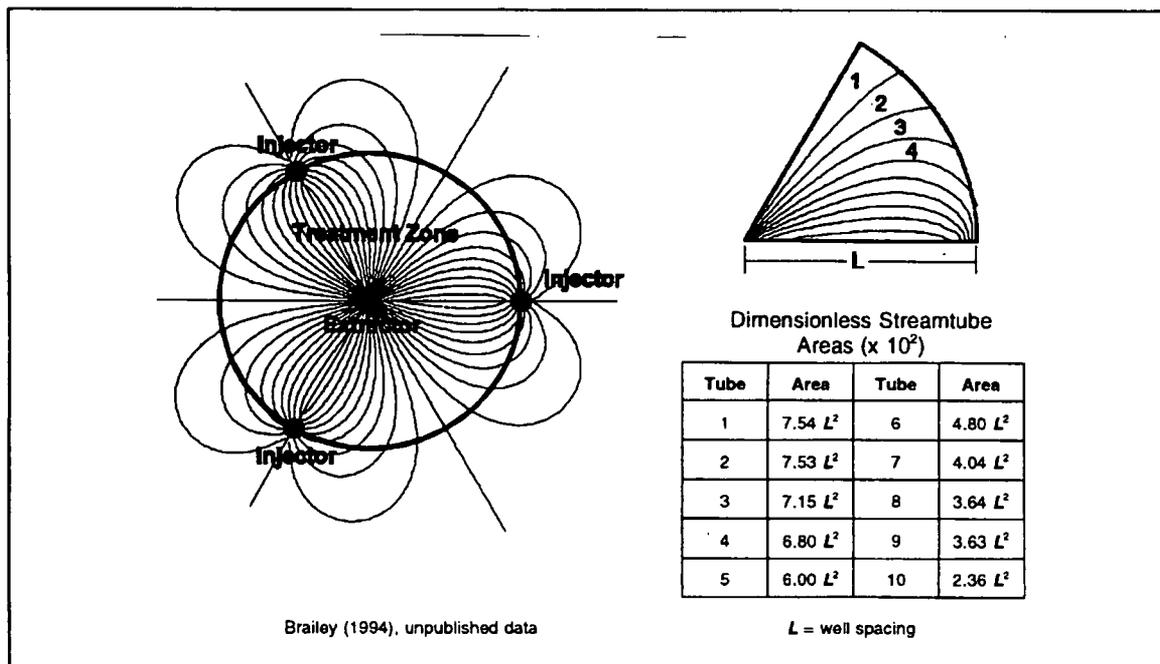


Figure 5-13. Plan view of streamtubes for a four-well system.

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To determine the required flow rate, use Equation 5-8 setting the time for one pore volume exchange ( $t_{ex}$ ) equal to the design criterion:

$$Q = \frac{4.52 L^2 b n_a}{t_{ex}} \quad (5-8)$$

Equation 5-8 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(25) For sites without impermeable surface covers, the three-dimensional flow geometry makes plan view representation difficult. Close to the water table, however, the flow geometry is similar to that shown in Figure 5-14. In cross section, the flow geometry for wells screened within the bottom third of the vadose zone, with well spacings of  $bA^{1/2}$  and  $1.6bA^{1/2}$ , are shown in Figure 5-14. These well spacings result in minor breakthrough of atmospheric air between injectors and extractors, but there is significant breakthrough between individual injectors. For wells screened within the bottom third of the vadose zone with a well spacing of  $1.6bA^{1/2}$ , the extraction rate calculated using Equation 5-8 should be increased by about 50 percent to account for breakthrough between individual extractors. For wells screened within the bottom third of the vadose zone with a well spacing of  $bA^{1/2}$ , the extraction rate should be increased by about 30 percent. The injection rate, however, should remain the same.

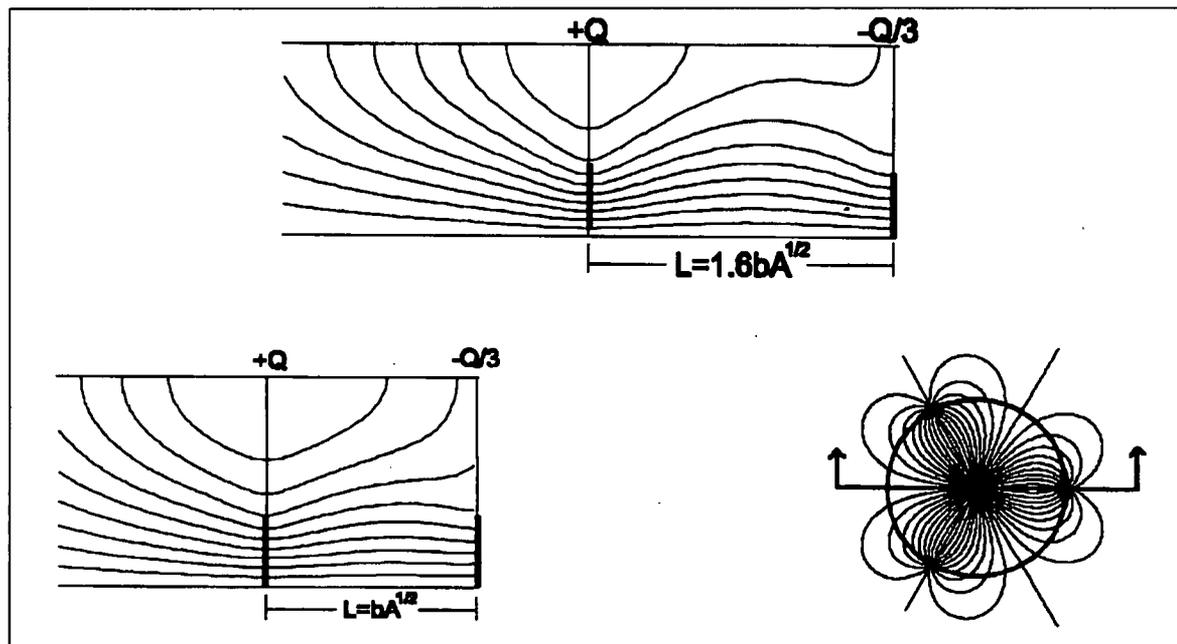


Figure 5-14. Streamtube profiles for a four-well system.

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(26) The amount of atmospheric breakthrough can be controlled by changing the well spacing, screened interval, and flow rate. Although smaller well spacings will result in less atmospheric breakthrough, streamtube modeling is required to evaluate well spacings other than those shown in Figure 5-14.

*e. Monitoring point locations and features.*

(1) In order to determine the effectiveness of an SVE/BV remediation system, monitoring probes are installed adjacent to extraction wells. The monitoring probes can be used to determine the vacuum, soil gas concentrations, or temperature at any one point.

(2) To determine the vacuum at a monitoring probe, the probe is sealed with a threaded removable cap or septum to maintain a vacuum within the probe. A vacuum gauge or manometer may be tightly threaded through the top of the probe to provide continuous readings, or a pressure transducer may be employed to provide more sensitive readings of applied vacuum.

(3) Soil gas contaminant concentrations may be measured within the probe by connecting a small vacuum pump to the probe through a valve, and pumping the soil gas to a field instrument equipped with a flame ionization detector (FID) or a photoionization detector (PID). Alternatively, the sample of the soil gas can be captured in a Summa canister, gas-tight syringe, or on a sorbent, and analyzed on an on-site or off-site gas chromatograph.

(4) Typically, monitoring probes are constructed with minimal screened intervals so as to characterize parameters at distinct depths. It is strongly recommended that data be collected in three dimensions to account for heterogeneity and anisotropy of various parameters and conditions. The probes should be installed in clusters with multiple intervals screened to evaluate the variation in parameters with depth. In many cases, driven or pushed probes may be used and these may be very cost effective provided an adequate seal can be demonstrated between the screened interval and the surface. For a single extraction well, the installation of at least two monitoring point clusters at locations that characterize the site heterogeneity is recommended. Within each cluster, at least two different depths should be monitored individually, and more than one cluster can be situated along a given radial. For larger sites with many extraction points, the ratio of monitoring point clusters to extraction points can be reduced to between 1 and 2, as careful location of the monitoring points can supply data for more than one extraction point. As the size of the site and the number of extraction wells increases, it is usually not necessary to provide two monitoring points for each extraction well, although a ratio of at least 1 is recommended. Monitoring probes are most appropriate in areas that are least likely to get adequate air throughput, such as stagnation zones between extraction wells. Vacuum measurements and soil gas samples taken in those areas are very important in evaluating the system performance. More intensive monitoring can be conducted at locations with high concentrations of contaminants and that represent typical hydrogeologic conditions at the site.

(5) If the soil is heated to induce faster contaminant removal, temperature probes may be used to measure the thermal gradients at known distances from the heating source. In installations of temperature probes at multiple depths, the thermometer devices should generally be separated from each other in the well bore by at least 3 meters using grout plugs at least 1 meter thick. Temperature measurements are particularly important for BV applications or SVE applications that use passive/active air injection to induce biodegradation. Since biodegradation rates and vapor pressure are both strongly sensitive to

temperature, it is important to monitor these data, especially in locations where large seasonal fluctuations in temperature occur.

*f. Integration with groundwater controls/free product recovery.*

(1) In general, SVE or BV systems are not economical for the removal of significant amounts of free product. SVE has, however, been used successfully to remediate thin (less than 15 cm) lenses of volatile LNAPL, such as gasoline. Many SVE systems are operated in conjunction with a groundwater and/or free product recovery system (see paragraph 3-2e, and EM 1110-1-4010). The design team must be aware of the need as well as the potential for effective integration of SVE/BV with liquid phase remedial technologies. Integrated approaches to remediation of soil and groundwater are preferable over those that address one medium and neglect contamination in another interrelated medium.

(2) A primary design consideration is that the controls for the vacuum/air movement system should be compatible in operating logic with the pumping controls for the groundwater pumping system. If one system has a set of automatic shutoffs, the other systems should be similarly equipped. If a telemetric data collection system is used, it should be capable of recording data from both systems.

(3) As an example, bioslurping systems incorporating multiple extraction points are controlled by logic systems that shuttle the applied vacuum from one extraction point to another when the well ceases to collect product and begins to pull water, and when soil O<sub>2</sub> levels rise to above 15 percent, indicating the soil is adequately aerated.

*g. Possible effects of nearby activities or contaminated sites.* Adjacent contaminated sites may play an important role in determining the well locations of an SVE/BV system for the site to be treated. The wells should be placed in a configuration which will effectively treat the site without inducing onsite migration of contaminants from offsite sources. A set of passive wells at the property line may be used to create an effective barrier to onsite migration. This "picket fence" should consist of a series of wells screened throughout the depths of concern and typically not less than 1.5 meters apart. The well spacing will be dictated by air permeability. The wells may also be used as monitoring points to demonstrate the effectiveness of the passive wells in preventing cross-contamination from offsite.

#### **5-4. Overall Pneumatic Considerations**

*a.* It is important to consider overall system pneumatics prior to designing and selecting individual system components. A suggested approach is briefly summarized below and subsequently examined in more detail.

Step 1. Develop a relationship for vacuum level versus airflow in the subsurface.

Step 2. Calculate the friction loss for the system components and piping for a range of flow rate.

Step 3. Develop a "system" curve by adding the frictional losses calculated in steps 1 and 2.

Step 4. Research and select a blower and determine the blower curve.

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Step 5. Predict the flow rate and vacuum level from the simultaneous (graphical) solution of the blower curve and the system curve.

Step 6. Balance the flows at each well, if necessary, and recalculate the vacuum levels.

(1) The first step has already been discussed. As mentioned in Chapter 4, site modeling or hand calculations based on pilot studies or bench-scale studies will allow the designer to predict the flow rate of air removed from the subsurface as a function of the vacuum (or pressure) level applied. Well efficiency for the vent must be considered in this step.

(2) The next step is to predict head loss through the system components for a range of flow rates. These calculations are fairly routine and not at all unique to SVE/BV systems. However, this manual will briefly discuss these calculations in order to lay the groundwork for further discussions that are more specific to the pneumatics of SVE/BV systems.

(a) The most common method of predicting friction losses in straight pipes is to use the Darcy-Weisbach equation:

$$h_f = (fL/d) (v^2 / 2g) \quad (5-9)$$

where

$h_f$  = friction loss

$f$  = friction factor

$L$  = length of pipe

$d$  = diameter of pipe

$v$  = average pipe velocity

$g$  = gravitational constant

The friction factor  $f$  is a dimensionless number that has been determined experimentally for turbulent flow and depends on the roughness of the interior of the pipe and the Reynolds number. Tables and charts have been developed to predict friction loss for a range of pipe sizes, liquids, and pipe materials (Spencer Turbine Co. 1987). Figure 5-15 is a friction loss chart that has been developed for inlet air at 294K and 101-KPa absolute pressure. Metric versions of these tables and charts are currently being produced in the industry and will be included as an addendum to this manual when available.

(b) There are two primary methods for estimating head losses through valves and fittings.

- Look up  $k$  values in tables (where  $k = fL/d$  and, therefore,  $h_f = kv^2/2g$ ) or

-

- Use tabulated values of equivalent length of straight pipe. For example, the resistance in a 150-mm (6-inch) standard elbow is equivalent to that of approximately 5 meters of 150-mm (6-inch) straight pipe.

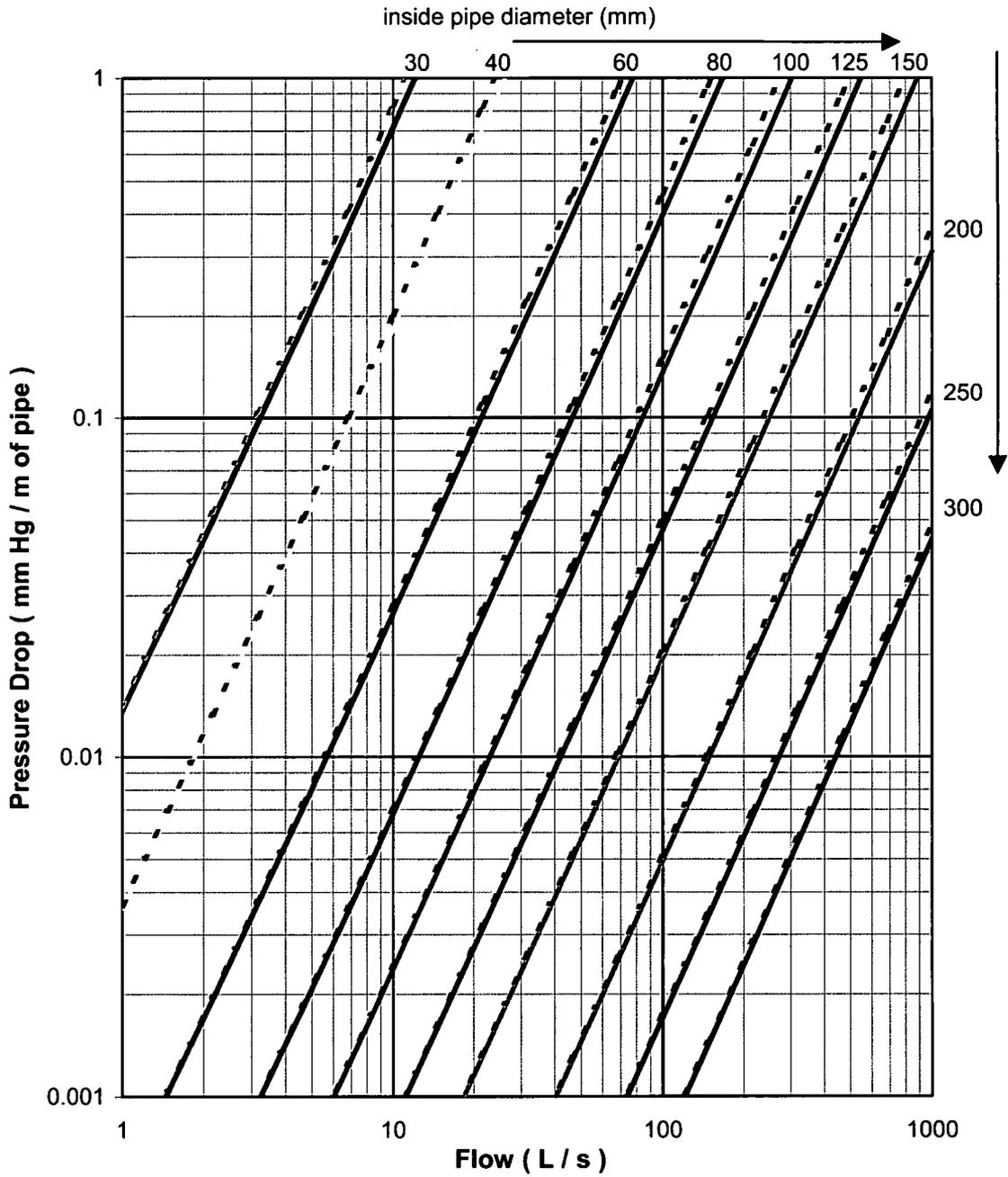
(c) The friction losses from the subsurface, the straight pipe lengths, and the valves and fittings are added together to obtain the total friction loss at a given vacuum level. This calculation is repeated for several flow rates to establish a system curve. Note that these calculations are performed assuming that the valves are fully open.

(d) The blower curve is then superimposed on the system curve as shown in Figure 5-16. Blower selection will be discussed further in paragraph 5-9. A specific blower would be selected based on mechanical, electrical, and pneumatic considerations. The pneumatic considerations, discussed in this section, are of prime importance. Notice the blower curve is negatively sloped and the system curve is positively sloped. The predicted flow rate and vacuum level obviously occur at the intersection of the two curves, representing the simultaneous solution of two equations.

(e) The predicted flow rate must exceed the design flow rate to allow flow control of multi-well systems by valves located at the inlet manifold. To establish the initial system curve, the total flow rate is specified but the flow rates at the individual wells are dependent variables. However, when the SVE/BV system is operated, the system would be adjusted to achieve a specified flow rate at each well. This adjustment causes an increase in vacuum level at the blower and a decrease in the total flow rate as shown in Figure 5-16. The designer must verify that the new flow rate and pressure are within the operating range of the blower.

●●●

### Friction Losses in Pipe for Air @ STP Conditions ( 20° C and 760 mm Hg )



\*Top line of pair for steel pipe and lower line for PVC pipe.

Figure 5-15. Friction Loss Chart.

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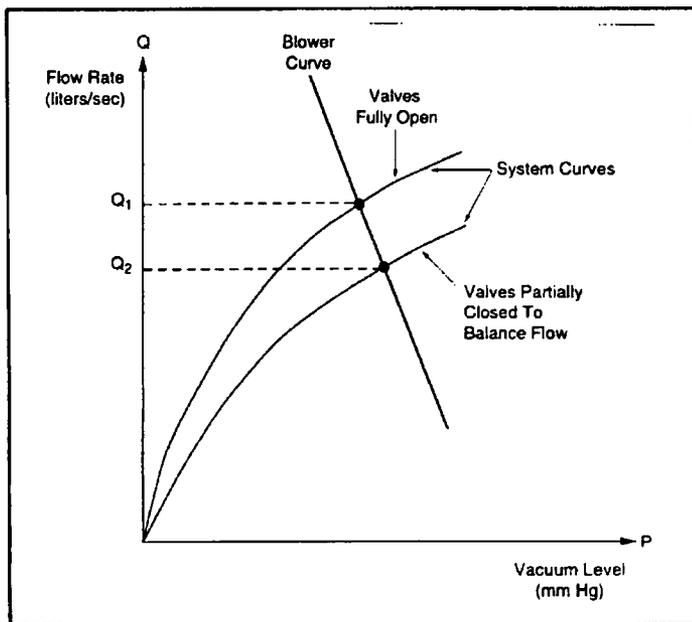


Figure 5-16. Typical SVE pneumatic analysis.

(f) This analysis demonstrates that if there are several geological units onsite 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.

*b. Numerical example of pneumatic analysis.* The following is a numerical example of a detailed pneumatic analysis for a network of three SVE/BV wells.

### Sample Calculation - Pneumatic Analysis

This is an iterative calculation; the head loss depends on the flow but the flow rate is unknown. As described in the previous section, first, a "system" curve is developed by plotting points over the flow rate range of interest. Each point on the system curve is generated by an iterative calculation. Second, a blower is selected and the blower and system curves are solved simultaneously. Third, an analysis is performed to determine to what extent the flow rates could be equilibrated.

(1) It was assumed that the relationship for the subsurface between the flow rate and the vacuum level induced at each wellhead is predetermined. For simplicity, the following linear relationship was assumed:

$$h = aQ \quad (5-10)$$

where

$a =$  a regression analysis coefficient. A more complex form may be chosen based either on theoretical considerations or on achieving the best fit for the empirical data

(2) Also, the piping network design (see Figure 5-17) must be established before performing this calculation. Nominal pipe sizes are usually estimated based on experience and rules-of-thumb. This aspect of the design process is also iterative. If, upon performing the pneumatic analysis, the friction losses are unacceptable, then the sizes and components of the system are altered, and the analysis is repeated.

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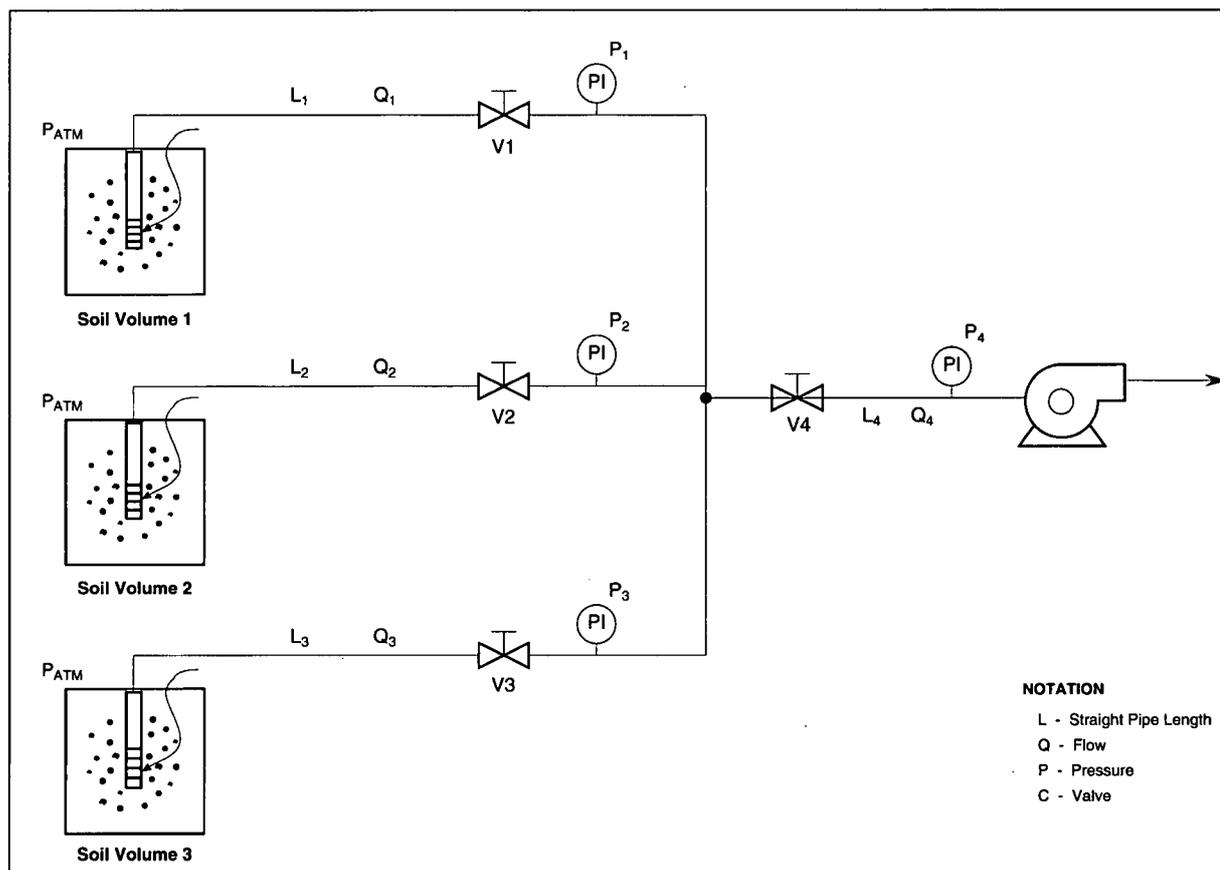


Figure 5-17. Piping network for pneumatic calculation.

(3) The spreadsheet, Table 5-1a, shows the details of the pneumatic analysis. Table 5-1a represents one point on the system curve. The density and viscosity of air were input. The total flow,  $Q_4$ , and the flow in pipelines  $Q_1$  and  $Q_2$  are assumed. The flow in the last line is determined by continuity,

$$Q_3 = Q_4 - Q_1 - Q_2 \quad (5-11)$$

(4) A nominal pipe diameter was selected for each line. Consequently, the velocity and the Reynold's number  $Re$  were calculated. The relative roughness ratio,  $\epsilon/D$ , was based on smooth steel pipe. The friction factor calculation was based on the Sacham equation:

$$f = \{-2 \log [(\epsilon/D)/3.7 - (5.02/Re) \cdot \log [(\epsilon/D)/3.7 + (14.5/Re)]]\}^{-2} \quad (5-12)$$

(5) To compute the frictional losses through fittings and fully opened valves, the equivalent lengths and quantities were tabulated. For each pipeline, the total length is equal to the length of the straight pipe plus the sum of the equivalent lengths (of straight pipe) of the valves and fittings.

$$L_{total} = L + \sum n \cdot L_e \quad (5-13)$$

where

$n$  = the quantity of each fitting

$L_e$  = the equivalent length

(6) The friction loss for an individual pipeline was calculated based on the Darcy-Weisbach equation (Equation 5-9). The total pressure loss is the sum of the pressure loss from the subsurface, the pressure loss through the system, and the pressure loss induced by closing valves.

(7) An iterative calculation was performed to develop the system curve. Notice from Figure 5-17 that all three lines merge at a single node. The pressure must be the same at this node regardless of the path. Therefore, the total friction loss must be the same through all three lines. To perform this iterative calculation, a total flow rate (Q4) was selected. Flow rate values for Q1 and Q2 are selected until all three pressure losses are equal. Then, the frictional loss through any of the three lines ( $h_1$  or  $h_2$  or  $h_3$ ) was added to the frictional loss in the combined line ( $h_4$ ) to get the total frictional loss. The results were tabulated (Table 5-1b) and the data were plotted in Figure 5-18. A blower curve was selected to match the system curve.

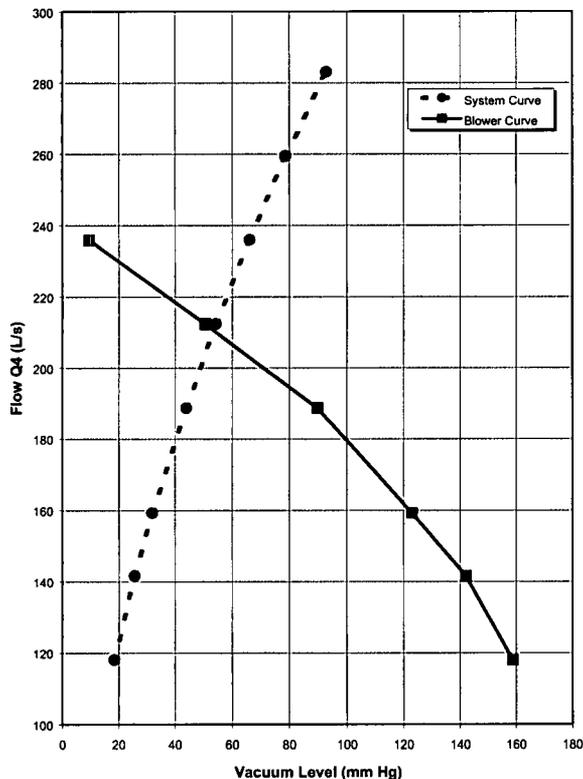


Figure 5-18. Results of pneumatic analysis.

(8) The system curve was developed assuming that the valves are in the fully open position. The final step of the analysis is to regulate the flow by closing valves. A summary of this step of the analysis is provided in Table 5-1c. Assume that it is desirable to operate each well at 64 L/s. The total flow for all three wells would be 192 L/s. By reading or interpolating the blower curve it can be determined that an 84.3-mmHg pressure loss must be induced at this flow rate. Since 10.9 mmHg are lost through line 4, lines 1 through 3 must all induce a loss of the remaining 73.4 mmHg. Recall that the pressure losses in lines 1 through 3 are identical. The surface and subsurface losses are subsequently subtracted from the total line loss to determine the pressure loss induced by closing the valve. For example, in the first line, 8.0 and 19.2 mmHg are subtracted from a total of 73.4 mmHg to obtain 46.2 mmHg. This analysis demonstrated that it is possible to achieve 64 L/s at each well.

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Table 5-1a

## Pneumatic Analysis for SVE System: Calculation Spreadsheet for a Single Point

| Constants                   |                         |          |              |         |                                 |
|-----------------------------|-------------------------|----------|--------------|---------|---------------------------------|
| Density =                   | 1.293 kg/m <sup>3</sup> |          | (at 0 deg C) |         |                                 |
| Viscosity =                 | 1.71E-05 (kg/m*s)       |          | (at 0 deg C) |         |                                 |
| Gravity (g)                 | 9.81 m/s <sup>2</sup>   |          |              |         |                                 |
|                             | LINE 1                  | LINE 2   | LINE 3       | LINE 4  | COMMENTS                        |
| Flow (L/s)                  | 78.8                    | 65.4     | 44.5         | 188.8   | Q3 = Q4 - Q2 - Q1               |
| Flow (M <sup>3</sup> /s)    | 0.079                   | 0.065    | 0.045        | 0.189   |                                 |
| Nom. Dia. (in)              | 4                       | 4        | 4            | 6       | Given                           |
| D [m]                       | 0.102                   | 0.102    | 0.102        | 0.152   | Pipe ID (sch. 40)               |
| Int. Area (m <sup>2</sup> ) | 0.008                   | 0.008    | 0.008        | 0.018   | Pipe area                       |
| Vel. (v) [m/s]              | 10                      | 8        | 6            | 10      | v = (Q/A)                       |
| Reynolds #                  | 7.5E+04                 | 6.20E+04 | 4.2E+04      | 1.2E+05 | Re = D*v*den./visc.             |
| e/D                         | 4.5E-04                 | 4.5E-04  | 4.5E-04      | 3.0E-04 | Steel pipe roughness            |
| F                           | 0.021                   | 0.022    | 0.023        | 0.019   | Friction factor (from eqn 5-12) |
| L (m)                       | 100                     | 250      | 150          | 50      | Straight pipe length            |
| Equivalent Lengths          |                         |          |              |         |                                 |
| 90 deg Elbow (m)            | 3.08                    | 3.08     | 3.08         | 4.63    |                                 |
| Tee (str. thru) (m)         | 2.05                    | 2.05     | 2.05         | 3.08    |                                 |
| Tee (Branched) (m)          | 6.13                    | 6.13     | 6.13         | 9.24    |                                 |
| Gate Valve (m)              | 0.82                    | 0.82     | 0.82         | 1.23    | Fully opened                    |
| Globe Valve (m)             | 34.75                   | 34.75    | 34.75        | 52.44   | Fully opened                    |
| Butterfly Valve (m)         | 4.6                     | 4.6      | 4.6          | 6.92    | Fully opened                    |
| Expansion (m)               | 1.58                    | 1.58     | 1.58         | 2       |                                 |
| Contraction (m)             | 0.82                    | 0.82     | 0.82         | 1.4     |                                 |

**Table 5-1a  
(Concluded)**

| Quantities                                     | LINE 1        | LINE 2        | LINE 3        | LINE 4        | From piping diagram                                |
|--|---------------|---------------|---------------|---------------|--|
| 90 deg Elbow                                   | 3             | 4             | 3             | 2             |  |
| Tee (str. thru)                                | 1             | 1             | 1             | 6             |  |
| Tee (Branched)                                 | 1             | 1             | 1             | 3             |  |
| Gate Valve                                     | 1             | 1             | 1             | 1             |  |
| Globe Valve                                    | 0             | 0             | 0             | 1             |  |
| Butterfly Valve                                | 1             | 1             | 1             | 0             |  |
| Expansion                                      | 0             | 0             | 0             | 1             |  |
| Contraction                                    | 0             | 0             | 0             | 1             |  |
| Total Equiv. Length (m)                        | 123           | 276           | 173           | 163           | $L + \sum(L \cdot n)$                              |
| Pressure Head<br>[meters of air]               | 123           | 196           | 61            | 111           | $hf = (f \cdot L \cdot v^2) / (2 \cdot D \cdot g)$ |
| Pressure Loss<br>[N/m <sup>2</sup> ]           | 1560          | 2480          | 770           | 1410          | $hf \cdot \text{density} \cdot g$                  |
| Pressure Loss<br>[mmHg]                        | 11.7          | 18.6          | 5.8           | 10.6          | $N/m^2 \cdot /133$                                 |
|  | <b>LINE 1</b> | <b>LINE 2</b> | <b>LINE 3</b> | <b>LINE 4</b> | <b>COMMENTS</b>                                    |
| <b>Subsurface pneumatic losses</b>             |               |               |               |               |  |
| Regr. Coef. (a)                                | 300           | 240           | 680           | 0             | From pilot study (given)                           |
| Subsurface Loss<br>[mmHg]                      | 23.6          | 15.7          | 30.3          | 0.0           | $h = a \cdot Q$                                    |
| <b>Pressure loss induced by closing valves</b> |               |               |               |               |  |
| Valve Loss                                     | 0             | 0             | 0             | 0             |  |
| <b>Total Loss<br/>[mmHg]</b>                   | <b>35</b>     | <b>34</b>     | <b>36</b>     | <b>11</b>     | <b>Surface + subsurface</b>                        |

**Table 5-1b**  
**Pneumatic Analysis for SVE System: Tabulated System and Blower Curves**

| Q1<br>[L/s] | Q2<br>[L/s] | Q3<br>[L/s] | Q4<br>[L/s] | h1,h2,h3<br>[mmHg] | h4<br>[mmHg] | System Curve Total h<br>[mmHg] | Blower Curve<br>[mmHg] |
|-------------|-------------|-------------|-------------|--------------------|--------------|--------------------------------|------------------------|
| 47.5        | 30.8        | 39.7        | 118.0       | 14.1               | 4.4          | 18.5                           | 158.75                 |
| 57.2        | 36.7        | 47.7        | 141.6       | 19.5               | 6.2          | 25.7                           | 141.94                 |
| 64.3        | 41.3        | 53.6        | 159.2       | 24.1               | 7.8          | 31.9                           | 122.9                  |
| 76.4        | 49.0        | 63.4        | 188.76      | 33.3               | 10.6         | 43.9                           | 89.64                  |
| 85.8        | 55.1        | 71.5        | 212.4       | 41.1               | 13.2         | 54.3                           | 50.43                  |
| 95.3        | 61.5        | 79.2        | 236         | 50.1               | 16           | 66.1                           | 9.34                   |
| 105.0       | 67.5        | 87.0        | 259.5       | 59.4               | 19.2         | 78.6                           |                        |
| 114.3       | 73.7        | 95.1        | 283.1       | 70.2               | 22.6         | 92.8                           |                        |

Note: The system curve is a plot of total head versus Q4.

**Table 5-1c**  
**Pneumatic Analysis for SVE System: Summary of Analysis with Valves Partially Closed**

|                        | Line 1 | Line 2 | Line 3 | Line 4 | Blower Curve |
|------------------------|--------|--------|--------|--------|--------------|
| Flow (L/s)             | 64.0   | 64.0   | 64.0   | 192.0  |              |
| Surface Loss (mmHg)    | 8.0    | 18.0   | 11.3   | 10.9   |              |
| Subsurface Loss (mmHg) | 19.2   | 15.36  | 43.52  | 0      |              |
| Valve Loss (mmHg)      | 46.2   | 40.1   | 18.6   |        |              |
| Total Loss (mmHg)      | 73.4   | 73.4   | 73.4   | 10.9   | 84.3         |
|                        |        |        |        |        |              |
| Flow (L/s)             | 68.0   | 68.0   | 68.0   | 204.0  |              |
| Surface Loss (mmHg)    | 8.9    | 20.1   | 12.6   | 12.3   |              |
| Subsurface Loss (mmHg) | 20.4   | 16.32  | 46.24  | 0      |              |
| Valve Loss (mmHg)      | 22.4   | 15.3   | -7.1   |        |              |
| Total Loss (mmHg)      | 51.7   | 51.7   | 51.7   | 12.3   | 64           |

(9) Now suppose that it is desirable to operate each well at 68 L/s. A similar analysis can be performed. However, in line 3 the desired total loss could only be achieved by inducing a negative pressure loss (a pressure gain) through the valve, which is not possible. This occurs because the blower will not operate at a high enough flow rate at the predicted head loss through line 3. Therefore, 68 L/s cannot be achieved at each well.

(10) The range of flow rates that are achievable with the proposed system are bound by the following constraints:

- Continuity at the node(s).
- The operating point must be on the blower curve above the intersection of the blower curve and the system curve.
- Only pressure losses (not gains) can be induced by closing a valve.

(11) From this analysis, it is possible to show that, for the example system, the system can operate at flow rates of 64 L/s at each of three wells (192 L/s total), but it is not possible to operate at 68 L/s at each well. The system would operate at a total flow of 211 L/s (the intersection of the two curves of Figure 5-18) without equalizing the flow. Therefore, roughly 19 L/s would be lost by equalizing the flows to 64 L/s.

(12) For more complex piping networks, it would be worthwhile to acquire software designed for this application. It would also be relatively straightforward to write a computer program to automate the iterative calculation. The calculation can be reduced to solving a series of nonlinear algebraic equations simultaneously. The Newton-Raphson method is a common numerical technique accomplishing this.

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(13) In summary, the pneumatic analysis was used to select a blower, determine the operating point of the system in the absence of flow regulation, and determine the effect of regulating the flow on the total flow. If the proposed treatment system or well spacing were not adequate, it would be modified. This analysis also shows the likely operating range of valves and the effects of altering piping sizes.

*c. Surface considerations.* Once the size of the blower has been determined, and the well configuration has been determined, a system must be provided to deal with the VOCs which reach the surface in the case of an SVE system. This concentration should be as high as possible to maximize the efficiency of the destruction system. Offgas treatment technologies are described in paragraph 5-12.

### 5-5. Well/Trench Construction

*a. Vertical extraction wells.* This section provides guidance for design and specification of vertical vapor extraction wells (Figure 5-19). Suggested sequence of specifications is provided in Chapter 6. Wells used for passive or active air injection, including BV vents, generally can be installed according to these requirements. Typical requirements are discussed under each topic.

(1) Standards. Standards for the materials and installation of extraction wells have been developed by such organizations as the American Society for Testing and Materials (ASTM), the American Water Works Association (AWWA), the American National Standards Institute (ANSI), the National Sanitation Foundation (NSF), and USEPA. 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  | D1785        | 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.  |
| USEPA | 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) Casing. New polyvinyl chloride (PVC) pipe, 100 to 150 mm (4 to 6 inches) in diameter, is normally used for SVE 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 vacuum drop inside well casing and screen diameters based on the pneumatic analysis procedures used for piping. Casing and screen diameters of 100 mm are adequate for most applications unless the formation is highly air permeable and individual well extraction rates are high (say 4 scmm or higher) in which case larger diameters may be appropriate. Other materials may be specified if contaminants, at expected concentrations, are likely to be damaging to PVC. Materials with appropriate physical properties and chemical resistance may be used in place of PVC where economical. Use heat-resistant materials such as steel if thermal enhancements to SVE may be 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 joints and o-ring seals. Table 5-2 indicates a range of acceptable sizes for extraction well materials including casing.

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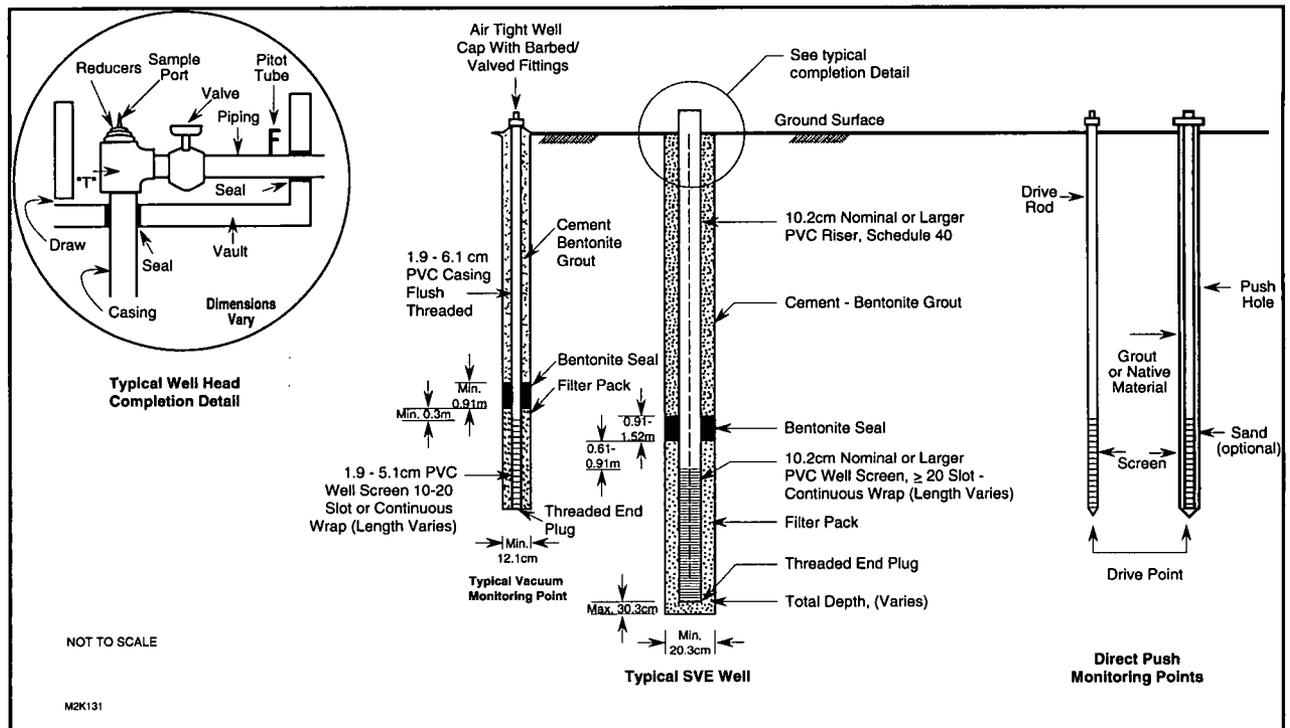


Figure 5-19. Extraction well/monitoring point construction details.

(b) Screen. Well screen is usually PVC with slotted or continuous wrap openings. Continuous-wrap screen is strongly preferred because the increased open area reduces the pressure drop across the screen and therefore reduces energy costs for the blower. Slot size is generally 0.5 mm (0.020 in.) but should be as large as possible to reduce the pressure/vacuum drop across the screen. Slot sizes of 1.01 mm (0.040 in.) or larger may be used. Larger slot sizes may, in a few cases, lead to increased entrainment of abrasive particles in the airflow. If the well will be used to recover groundwater or other liquids, the slot size must be chosen based on formation gradations, as described in Driscoll (1986). Screen with flush-threaded joints and o-ring seals are preferred.

(c) Filter pack. Pack material should be a commercially available highly uniform gradation of siliceous sand or gravel with no contaminants (chemical or physical). Choose a uniformity coefficient,  $C_u$ , of 2.5 or less. The actual gradation should generally be based on the formation grain size and the screen slot size. Coarser material may be used; however, coarser gradations may, in a few cases, lead to increased entrainment of abrasive particles in the airflow. If the well is to be used to recover liquids as well as air, the filter pack must be sized appropriately according to methods outlined in a text such as Driscoll (1986).

**Table 5-2**  
**Extraction Well Materials**

| Components     | Operating Size Range                |                                      | Comments  |
|----------------|-------------------------------------|--------------------------------------|---|
|                | Metric                              | English                              |   |
| Casing         | 50 mm<br>100 mm<br>150 mm           | 2 inch<br>4 inch<br>6 inch           | Sch 40<br>Larger diameters should be used where vacuum losses inside well may be high |
| Screen         | 50 mm<br>100 mm<br>150 mm           | 2 inch<br>4 inch<br>6 inch           | Sch 40<br>0.5 mm or larger slots  |
| Filter Pack    | $C_u \leq 2.5$                      |                                      | Refer to paragraph 5-4a(2)(c)   |
| Piping         | 50 mm<br>100 mm<br>150 mm<br>200 mm | 2 inch<br>4 inch<br>6 inch<br>8 inch | Sch 40  |
| Valves (Ball)  | 50 mm<br>100 mm<br>150 mm<br>200 mm | 2 inch<br>4 inch<br>6 inch<br>8 inch | Sch 40  |
| Joints (Elbow) | 50 mm<br>100 mm<br>150 mm<br>200 mm | 2 inch<br>4 inch<br>6 inch<br>8 inch | Sch 40  |

(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 obviously 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 of bentonite powder), with less than 18 liters of clean water. Reference ASTM C 150 in the specification 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 a size appropriate for the casing and borehole. These are recommended for holes greater than 6 m deep. Select centralizers made of material that will not lead to galvanic corrosion of the casing. Stainless steel centralizers are recommended with PVC or stainless steel casing.

(f) Bioventing wells are constructed with essentially the same materials as SVE wells.

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(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, the 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. Require sampling of soils at regular intervals, at least every 1.5 meters; sometimes, continuous sampling is appropriate. Samples should be obtained by appropriate method such as split spoon sampler or thin-walled tube according to ASTM D 1586 or D 1587, respectively. Sampling can also be conducted using direct push methods, if such methods are also being used for monitoring point installation. Consider sample volume requirements when specifying the sampling method. Require sampling for chemical and physical analyses be done according to an approved sampling and analysis plan. Strongly recommend 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, include observations of features relevant to air transmission, such as shrinkage cracks, root holes, thin sand layers, and moisture content.

(c) Borehole diameter and depth. Normally, the diameter is at least 101 mm (4 inches) greater than the diameter of the casing and screen to allow placement of the filter pack. The depth of the borehole should be based on the screen depth. The borehole should only extend to 0.3 meter 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. To maintain plumpness and alignment, the string should not be allowed to rest on the bottom of the hole. Centralizers should be placed on the casing at regular intervals if the depth of the well exceeds 6 meters.

(e) Filter pack placement. Filter pack should be placed around the screen to some level above the top of the screen, normally about 1 meter. Filter pack is normally placed dry by pouring down a tremie pipe. The tremie pipe, a narrow pipe with a hopper at the surface, is used to prevent bridging of grains in the annulus and is kept near the top of the pack material during placement. Store and handle the pack material carefully 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 meters 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 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. Place the high-solids bentonite grout by tremie pipe. Cement grout should also be pumped into annular space via a side-discharge tremie pipe and the pipe should be kept submerged in the grout during grout placement. If the grout is to be placed to a depth of less than 4.5 meters, 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 tight. 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. Establish the horizontal coordinates of the well by survey. Survey the elevation of the top of the casing if the well intercepts groundwater and the water elevation would be of interest. The accuracy of the surveys depends on the project needs, but generally is to the nearest 0.3 meter (1 foot) for the horizontal coordinates and the nearest 0.003 meter (0.01 foot) for elevation.

(i) Dual recovery. If groundwater has been impacted, the same well may be used for vapor and groundwater extraction (paragraph 3-2*d*). 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.

(j) Bioventing Wells. The installation techniques for bioventing wells are essentially the same as for SVE wells.

*b. 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 will be obvious differences in size.

(a) Casing. Generally, 20- to 50-mm (3/4- to 2-inch) 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 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-inch) diameter) but can be ordered. Slot sizes smaller than those typically used for extraction wells may be appropriate for monitoring points (i.e., 0.5- to 1.01-mm or 0.010- to 0.020-inch slots). Other "screen" types can be used. Options include slotted drive points, porous points or, for short-term use, even open-ended pipe.

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(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 SVE/BV 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 inches) larger than the screen/casing to allow placement of the filter pack. This obviously would not apply to points placed by direct-push methods. Allow adequate room for proper installation if multipoint monitoring systems are to be used. Multipoint 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 SVE/BV system or other remedial actions.

(d) Screen and casing placement. Casing and screen is normally placed by methods similar to those used to install SVE/BV extraction wells; however, direct-push techniques are rapid alternatives for placing monitoring points to the desired depths. Actual means of placement is dependent on the system, materials used, and site geology.

(e) Filter pack, seal, and grout placement. The procedures for sealing the well would generally be the same as those used for SVE/BV wells. Monitoring points placed using direct push techniques are subject to leakage along the drive casing or tubing if care is not taken to assure either a tight seal with the native soil after driving or in placement of the backfill/grouting of the annular space. Since the method of placement varies significantly depending on the equipment used, the project personnel responsible for the well construction must assure that the procedures used will result in a tight seal. See Figure 5-19 for typical installations using direct push methods. Use of drive points connected to the surface via flexible tubing placed loosely in the hole is not acceptable; in these cases, grouting above the screened drive point is required. Use of rigid pipe or casing is preferred. Multi-port monitoring systems require careful placement of seals between the monitored intervals to prevent "short-circuiting" between the various intervals.

(f) Surface completion. Complete the monitoring points with a suitable barbed/valved sampling port or septum attached by threaded connection to an appropriate end cap. Attach the cap 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. Each monitoring point must be clearly and permanently labeled with ID number and depth, especially any point constructed using flexible tubing grouted in a direct push hole since verifying the depth is often problematic for this type of construction.

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

c. *Vapor extraction trench.* Vapor extraction trenches are often used at sites with shallow groundwater or near-surface contamination; thus, the depth of excavation is often modest. Consider placing multiple pipes in the same trench, each with a separate screened interval, 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 5-20 illustrates a typical horizontal vent well design.

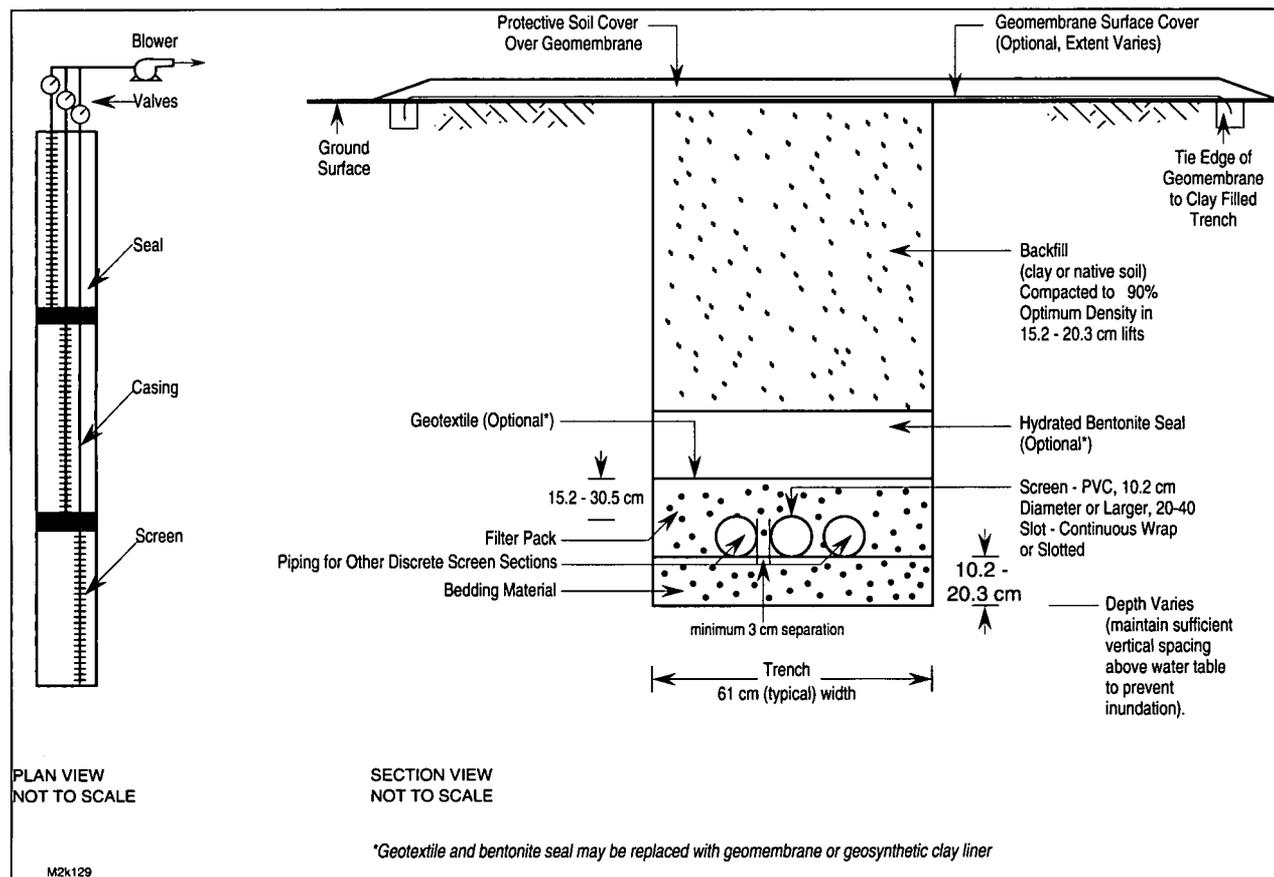


Figure 5-20. Typical horizontal vent well design, plan and section views.

(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.

(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 appropriate ASTM standards for PVC pipe or ASTM D 3350 for polyethylene plastics pipe and fittings materials. The casing can be joined by

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threaded coupling or thermowelds, as appropriate for the material. Pipe sizes of 101 to 203 mm (4 to 8 inches) are often used. The actual diameter should be sized to distribute the applied vacuum uniformly along the length of the screen. This may result in use of larger diameters than typically used in vertical wells because of the potentially larger flow rates. Larger pipe sizes allow easier access for surveys and maintenance.

(b) Screen. Given the generally longer screened intervals in horizontal applications, air entry velocities are generally lower and well efficiency is less of a concern. Thus, the screen open area can be somewhat lower than is needed in vertical wells. Although continuous-wrap screen is still preferred, successful systems have also used slotted pipe. In order to provide greater degree of flexibility in control of the system where the length of trench is great (say more than 30 m), the designer should use multiple screened intervals, each connected to the blower(s) via a separate run of blank pipe. Each section of screen should be separated from the other sections through the use of trench seals composed of cement grout or clay. (Refer to Figure 5-20). If slotted pipe is specified or allowed, the specification should require a minimum open screen area. Piping and screen lengths are generally greater in trench applications and vacuum loss along the screen must be considered. Avoid using drain pipe wrapped with geotextile because of the potential for fine material to plug the geotextile. Slot size can be quite large, 1.0 mm (0.040 inch) or larger, because the lower air velocities reduce the potential for entrainment of small particles. Screen can be joined by threaded couplings or thermowelded. For some horizontal well applications, a prepacked well screen is appropriate. Prepacked screens are really two screens enclosing preselected filter pack material. The use of prepacked screen can overcome the difficulties of installing filter pack within a horizontal well.

(c) Bedding material/filter pack. Generally, the guidance for specifying filter pack in SVE/BV wells applies for trenches, but somewhat coarser material may be needed for a secure bedding for the pipe and screen. A reference to ASTM D 2321 may be appropriate. Filter material placed above the water table generally need not be sized for the formation, and can be quite coarse.

(d) Cover and seal material. Native material may occasionally be used as backfill above the filter pack in an excavated trench. Given that vapor extraction trenches are typically used at sites with shallow groundwater, low-permeability material is preferable to enhance the lateral vacuum influence of the trench. Require the use of bentonite, clay, a geomembrane, or a geosynthetic clay liner, if appropriate.

(e) Geotextile. A geotextile may be needed to separate the filter pack from native material or clay backfill in an excavated trench.

(f) Marking tape and locator strips. Specify a locator strip specifically manufactured for marking underground utilities. This tape is made of colored polyethylene backed with foil or containing embedded wire that allows others to locate the trench at later dates. This would not be applicable for drilled horizontal well installations.

(2) Installation. Installation methods vary significantly depending on excavation method.

(a) Excavation methods. Methods used to install trenches or other horizontal installations include standard earth-excavating equipment (e.g., backhoe), trenching machines, horizontal drilling techniques, and pipe jacking/microtunneling. Given this wide variety, it may be desirable to specify only the pipe, screen, pack materials, and an ultimate pipe alignment and depth. This would allow the contractor the option to propose what might be the most cost-effective method; however, the trenching technique used by

the contractor must provide an adequate filter placement around the collector pipe. Note that horizontal drilling, pipe jacking, etc. reduce the amount of disturbed material and minimize both the potential for worker exposure and disruption to surface features. Many horizontal drilling techniques require drilling fluids that may not be appropriate for vapor extraction techniques.

(b) Soil sampling and logging. If open excavation techniques are used, a graphical log of the materials encountered in the trench should be prepared, including the description of the materials according to ASTM D 2488. Other excavation methods will require some log of the materials encountered at different stations and would usually be based on cutting returns from the trenching machine or drilling. Other sampling should be done as needed according to an approved sampling and analysis plan.

(c) Trench dimensions. The trench dimension should be wide enough to allow preparation of the bottom of the trench and placement of the pipe. Normally, the trench width is limited to the pipe diameter plus 600 mm. If the material to be trenched is contaminated, a smaller trench reduces the volume of material to be disposed or treated as waste. Compliance with Occupational Safety and Health Administration and USACE requirements is mandatory. If a horizontal drilling method is used, some annular space between the borehole and the screen should be required in a manner similar to vertical wells. The use of a prepacked well screen may require less annular space.

(d) Trench bottom preparation and pipe placement. The bottoms of the excavated trenches must be prepared before placement of pipe and screen. The trench must be leveled to the required grade to provide uniform bearing for the pipe. A bedding layer of filter pack material 100 to 200 mm thick should be placed and compacted before pipe and screen placement. Unstable materials should be removed. The pipe and screen should be placed in a way that prevents entrapment of filter pack or native material inside the pipe. The joining of sections of the pipe and screen must be done in a manner consistent with the material and manufacturer's recommendations. A clean-out or access port for the pipe should be provided to allow for later surveys and maintenance of the screen and casing. If the trench is to be installed to below the capillary fringe or the anticipated zone of upwelling, dewatering or dual recovery may be necessary.

(e) Filter pack placement. Filter pack placement is relatively simple in open trenches, but much more difficult in drilling or jacking operations. Compaction of the filter pack material should not be done within 150 mm to 300 mm of the pipe and screen. Some trenching machines place the pipe and filter pack material as it progresses. In these cases, it is important to verify that the machine is placing adequate filter pack around the screen. For horizontal drilling applications, various methods exist for placing filter pack, the most common and probably desirable of which is the use of the prepacked screen. The native material is allowed to collapse back upon the prepacked screen.

(f) Backfilling and compaction. The remainder of an excavated trench is backfilled with the appropriate material. Placement of a geotextile between the filter pack and backfill may be appropriate if there is a significant difference in grain size between the two materials. Backfill should be placed in 150- to 200-mm lifts and compacted to approximately 90 percent optimum standard density, determined by ASTM D 698, if cohesive materials are used. A bentonite seal can be used in conjunction with the backfill to further limit short-circuiting. A locator strip should be placed within 0.5 meter of the surface.

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## 5-6. Piping, Valves, and Manifold System

The proper selection and specification of piping materials plays a major role in the success of SVE or BV remediation. The materials sizes and configuration of piping must be carefully planned to avoid costly operating problems, as described below. The manifold system, which is composed primarily of piping and valves, is also discussed.

### *a. Piping.*

Piping for SVE/BV systems typically includes vacuum lines, pressure lines, sampling lines and condensate lines. Catalytic or thermal oxidizers (for offgas treatment) may also have fuel supply lines. The following major issues must be considered when designing a piping system: pressure limitations, temperature limitations, insulation, mechanical considerations, pneumatics and hydraulics, electrical grounding, and chemical compatibility.

(1) Pressure limitations: The design pressure must not exceed the maximum allowable limits for the piping system minus some reasonable factor of safety (i.e., 50 percent). Pressure relief valves should be included where required as per ANSI B31.3, Section 301.2. 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 is likely to ever be exerted in the context of SVE/BV, such usage appears to be well within the safe range of operation under the provision of appropriate pressure/vacuum relief. When using flexible hose lines on the vacuum side of the system, 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 SVE/BV systems. Temperature limitations of the material must not be exceeded. Plastic piping should not be used on the blower discharge; in the event that the blower overheats, the piping may melt. Outdoor installations of non-insulated above ground plastic piping should be evaluated in accordance with a document that was produced by the Plastic Pipe Institute (PPI) entitled PPI AW-32 TR21 Thermal Expansion and Contraction of Plastic Pipe (PPI 1974).

(3) Insulation: Insulation and heat tracing can be used to prevent unwanted condensation in piping as described in paragraph 5-6. Insulate high temperature incinerator components to prevent burn hazards.

(4) Mechanical stress: The supports should be designed and spaced in accordance with ANSI/MSS SP-58, -69, -89, and -90.

(5) Pneumatics and hydraulics: Overall system pneumatics were discussed in paragraph 5-4b. 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 meters per second are recommended for pumped condensate lines.

(6) Electrical grounding: If the SVE system will handle potentially flammable organic vapors, then the designer must ensure that the piping is properly grounded. Even if an explosion-proof blower and motor

are being used, ignition of an organic-rich vapor stream it is still possible (e.g., static electricity may build up inside piping that is not grounded, and a spark may be released). Where grounding is required, conductive piping materials (e.g., steel) are usually used. In-line flame arrestors can also be used to prevent a flame from moving through piping and other equipment. When placed near potential ignition sources (e.g., thermal oxidizers), flame arrestors can be used to protect other parts of the SVE system from fire or explosion.

(7) 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.

*b. Valves.*

(1) Valving is utilized in SVE/BV systems for flow rate control and on/off control. A typical SVE/BV system will have a flow control valve on each extraction or injection line.

(2) 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 SVE/BV 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.

(3) 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.

(4) 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 designer calculates  $C_v$  at the maximum and minimum flow rates required. The calculated range of  $C_v$  values must fall within the range for the valve selected.

(5) During the mechanical layout of the system, assure that the valves are accessible. Number and tag the valves. To avoid ambiguity, refer to the valves by number in the design and in the O&M manual.

(6) Check valves are sometimes needed between the well and the pump to prevent air from being drawn backward when the pump is shut off. Under higher vacuum, this can affect a variety of in-line readings, particularly if a carbon canister is being used for air treatment. If multiple wells are in service, each well may need a separate valve. The following is a brief description of several other valves commonly employed for SVE/BV systems (Figure 5-21):

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(a) Ball valve - Also 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 small 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.

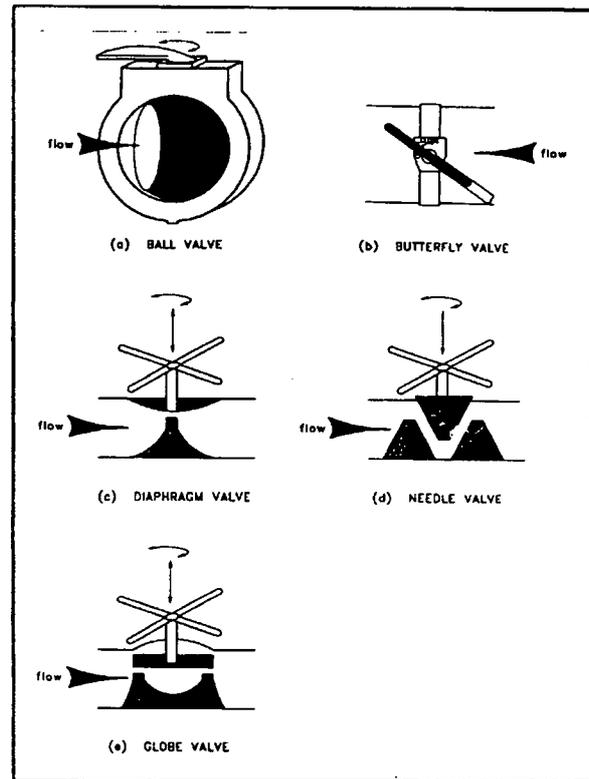


Figure 5-21. Valve schematics.

c. *Manifold system design.*

(1) A manifold system interconnects the injection or extraction wells into a single flow network prior to being connected to the remainder of the SVE/BV system (refer to Figure 5-22). A manifold system will include a series of flow-control valves, pressure and airflow meters, and VOC sampling ports at each wellhead, and 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.

(2) The manifold system should also have a manual air control valve to bleed fresh air into the SVE/BV pump system to reduce vacuum levels and temperatures within the motor/blower. Air control valves also control the applied vacuum in the subsurface and are

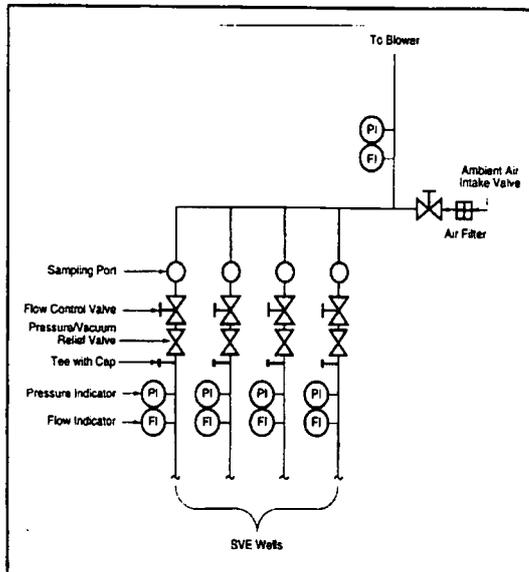


Figure 5-22. Typical manifold system.

used to start the vacuum system from a condition of zero applied vacuum. These valves should be of a type which will permit

adequate control of the airflow (globe, butterfly, needle, or ball valve designs work well). Also, a pressure/vacuum relief valve may be included in the manifold to protect the piping.

(3) The number of tees and joints within the pipe runs from the extraction wells to the manifold system should be minimized to reduce piping head losses. Angles within the solid runs should be kept above 135 degrees to reduce any air or vacuum restrictions within the pipe chases.

#### 5-7. Condensate Control

*a. Need for control.* Condensate controls are often necessary for SVE/BV systems to prevent unwanted liquids from accumulating in piping, blowers, or air emission control devices. The condensate controls remove moisture and store the liquid prior to disposal.

*b. Causes of condensation.* The soil vapors extracted from the subsurface are typically at or near 100 percent relative humidity. A subsequent decrease in temperature or increase in pressure will cause condensation. This condition is frequently encountered under winter conditions, or at any time or location that the aboveground piping is cooler than the temperature in the portion of the subsurface through which the gas has passed. Also, in cases where the water table is close to the surface or when a perched water table is present, water droplets may become entrained in the vapor stream, or free water may be drawn into the air-water separator. Piping between the vent wells and the blower should be sloped toward the vapor/liquid separator ("knockout") to prevent condensate from collecting in the piping.

*c. Overall design considerations.* The following paragraphs discuss (1) the effects of condensation on the overall design, (2) a method for estimating condensate generation, and (3) design issues involving air/water separators and condensate collection.

(1) Condensate control relates in various ways to the overall design of an SVE/BV system and needs to be considered not just with respect to the design of the condensate control devices. For a long-term SVE/BV system the best approach is often to minimize condensation by assuring that the relative humidity of the vapor stream does not exceed saturation, in which case, depending on cost, the SVE/BV system components could be located in a heated building (paragraph 5-14). A building heated to 20 °C would be sufficient. The lateral lines connecting the wells to the inlet manifold should either be buried or heat traced and insulated. Due to inefficiencies in converting electrical energy to mechanical energy, a vacuum blower will significantly heat the air stream, thereby lowering the relative humidity. This "thermal boost" should be considered and taken advantage of in the design of the SVE system.

(2) It is necessary, based largely on condensate control considerations, to decide whether to locate the blower upstream or downstream of activated carbon equipment if activated carbon is included in the design for offgas treatment. Ideally, the air flowing through the carbon would have a relative humidity of 40% at 27°C and low pressure. Lower temperatures thermodynamically favor adsorption of organics because adsorption is exothermic. However, a reduction in temperature increases the relative humidity. Generally if the blower is located upstream of the carbon, a small temperature rise (e.g., a rise of 5-15°C) would be favorable because of humidity reduction, but a large temperature rise (i.e., a rise of 50°C) would be unfavorable for thermodynamic reasons cited above. In addition to condensate control issues, the designer must also consider the pressure limitation of the vessels and the capacity of the blower. Since there is an absolute limit to the amount of vacuum that can be created and significant head loss can occur in the carbon vessel, it may be preferable to locate the carbon downstream of the blower. Also, most carbon vessels will

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be able to withstand greater positive pressure than vacuum, which would also argue for locating the carbon downstream of the blower.

(3) For short-term installations and pilot studies, it may not be practical to keep the system heated in order to avoid condensation. In those cases, air/water separators must be adequately sized to collect the moisture. For pilot units operating in the winter, it is worthwhile and typically necessary to insulate carbon vessels. In general, the air/water separator should be kept as cool as possible to generate condensation and the downstream system components should be kept warm through insulation and/or heat tracing.

*d. Condensate quantity estimation.* Prior to designing an SVE/BV system or conducting a pilot study, the engineer should estimate the rate at which condensate will be generated. An estimate can be obtained by using psychrometric charts which are readily available in standard thermodynamic references, as shown in the sample calculation below:

#### Sample Calculation - Condensate Quantity

Estimate the rate of condensate generation for a 2-day pilot study conducted during the winter using a 236 L/S (500 CFM) SVE system. The average ambient temperature will be 272 K and the absolute pressure in the air/water separator will be 0.5 atm.

Assume air is extracted at 100% relative humidity and 286 K. From a psychrometric chart,

Conc. of water vapor =  $8.86 \times 10^{-3}$  kg/kg air (at 286 K)

Conc. of water vapor =  $3.43 \times 10^{-3}$  kg/kg air (at 272 K)

Subtracting, Condensate =  $5.43 \times 10^{-3}$  kg/kg

Use the Ideal Gas Law to estimate the air density.

Density =  $PM/RT = (0.5 \text{ atm}) \times (29 \text{ kg/kg-mole}) / (0.0821 \text{ L-atm/ g-mole K}) \times (272 \text{ K}) \times (1,000 \text{ g-mole/kg-mole})$

Density =  $6.49 \times 10^{-4}$  kg/L

where  $M = 29 \text{ kg/kg-mole}$

The flow rate times the concentration of the condensate in the air (based on the air density in the piping) yields:

$(5.43 \times 10^{-3} \text{ kg/kg}) \times (6.49 \times 10^{-4} \text{ kg/L}) \times (236 \text{ L/s}) \times (86,400 \text{ s/day}) \times (1 \text{ L/kg}) = 71.9 \text{ L/day (19 gal/day)}$

Therefore, 144 liters would be generated in 2 days. Supply one 55-gallon drum to store condensate for the pilot study. This allows for an additional 64 liters (17 gallons) due to entrainment.

This example demonstrates that significant volumes of condensate can be generated even in short-duration pilot studies.

*e. Design aspects of air/water separation.*

(1) This manual will be concerned solely with physical- or inertial-type air/water separators. These are the types most commonly used for SVE/BV systems. It is possible (although not typically practical) to use refrigerated air dryers or regenerative desiccant dryers. Refrigerated dryers remove moisture from air by chilling the air to the point where water condenses to a liquid and drains away. Regenerative desiccant dryers adsorb water vapors in a desiccant such as anhydrous sodium sulfate or activated alumina. Inlet air is dried in one vessel while desiccant is regenerated in another vessel. Although not typically used for SVE/BV applications, these types of dryers should be considered if highly effective moisture removal is required.

(2) Inertial separators are generally used for air/water separation in SVE/BV systems. By imparting centrifugal force to the water droplets, these separators can collect small water particles. Typically particles as small as 20 microns can be removed. The gas stream is injected into a cylinder 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.

(3) Manufacturers of inertial air/water separators typically size the units according to flow rate. A detailed discussion of centrifugal separation can be found in Perry's Handbook (Perry and Green 1984). Pressure drops through the separator can be approximated by the following empirical equation (Corbitt 1990). This equation assumes a rectangular inlet.

$$F = KB_c H_c / D_e^2 \quad (5-14)$$

where:

$F$  =cyclone friction loss expressed as fraction of velocity head

$K$  =an empirical constant, typical value = 16

$B_c$  =gas inlet width (m)

$H_c$  =gas inlet height (m)

$D_e$  =gas outlet diameter (m)

$$\text{Head loss} = F (V^2 / 2g) \quad (5-15)$$

(4) The condensate separator should be able to withstand the highest vacuum that a blower is capable of exerting. Condensate separators need pumping systems or a manual method to remove the separated water. Pumps must be both leakproof and able to provide sufficient head to offset the vacuum in the separator vessel. Condensate treatment and disposal methods are discussed in paragraph 5-13.

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### 5-8. Particulate Filters

*a.* Particulate filters are typically installed between the condensate removal system and the blower inlet. Although the condensate removal system will decrease the concentration levels of airborne particulates, 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.

*b.* Cartridge air filters are often used for this type of application. Filter elements are manufactured from a variety of elements including pleated paper, felt, or wire mesh. Paper elements are inexpensive and typically disposable. Felt and wire mesh filters may be washed. The filter is selected based on the airflow rate, the 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 difference across the filter.

### 5-9. Blower Silencers and Acoustics

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

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

*c.* Also, if the SVE/BV system is located within a building, shed, or trailer, wall material selection should consider acoustical properties. Complete tables of absorption coefficients of various building materials versus frequency may be found in books on architectural acoustics.

*d.* Address site specific hearing protection requirements in the site safety and health plan. Refer to Section 05.C of EM 385-1-1 for USACE hearing protection and noise control requirements. Require the contractor to measure sound pressure levels in work areas near noisy equipment. Ensure the contractor enrolls employees with potential exposure in excess of 85dB(A) (TWA) in a hearing conservation program meeting 05.C.03 requirements and that employees with exposure in excess of 90 dB(A) are provided with hearing protection or are protected by administrative (time limitation) means.

### 5-10. Blowers and Vacuum Pumps

The pneumatic considerations involved in blower selection have been discussed in paragraph 5-4b. The following paragraphs focus primarily on mechanical considerations and the interrelationships among the blower design variables.

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a. *Mechanical categories of blowers.* This section will describe the following three types of blowers commonly used for SVE/BV systems: regenerative blowers, rotary lobe blowers, and liquid ring vacuum pumps, which are shown schematically in Figure 5-23. These blower types are most applicable for low, medium, and high vacuum applications, respectively. Although there are many blowers that could possibly be used for SVE/BV systems, these three types are representative of those frequently encountered. Vendors will typically have several models of the same blower series, each with a different flow capacity. All three of these blower types are generally available in flow rate ranges required by SVE/BV systems -- 80 m<sup>3</sup>/hr (47 cfm) to 8,000 m<sup>3</sup>/hr (4,700 cfm). Variable speed blowers should also be considered for use at sites where the flow rate required will decrease with time.

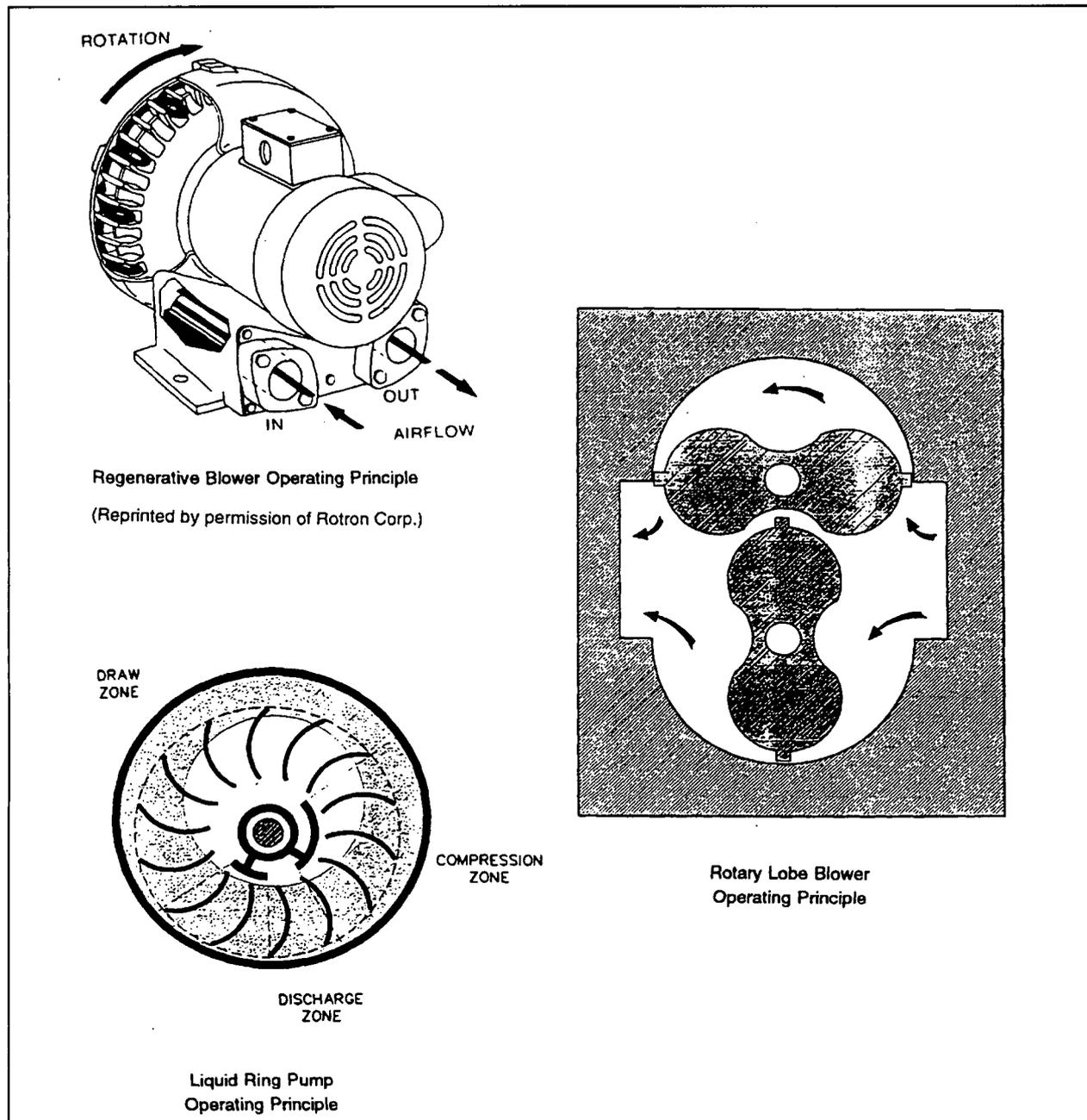


Figure 5-23. Blower schematics.

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(1) Regenerative blowers. These blowers are typically employed for SVE/BV applications requiring less than 203.2 cm (80 inches) of water vacuum. Regenerative blowers are compact and produce an oil-free airflow. The principle of operation is as follows: A multistage impeller creates pressure through the use of centrifugal force. A unit of air enters the impeller and fills the space between two of the rotating vanes. The air is thrust outward toward the casing but then is turned back to another area of the rotating impeller. This process continues regenerating the pressure many times until the air reaches the outlet.

(2) Rotary lobe blowers. These blowers are typically used for a medium range of vacuum levels (roughly 51 to 457 cm or 20 to 180 inches of water). During operation of these blowers, a pair of matched impellers rotate, oriented in opposite directions, trap a volume of gas at the inlet and move it around the perimeter to the outlet. Rotation of the impellers is synchronized by timing gears which 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 the 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.

(3) 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 and compressed by the liquid ring as the gas is forced radially inward toward a central discharge port. After each revolution the compressed gas and accompanying liquid are discharged. Vacuum levels close to absolute vacuum (i.e., absolute pressure equals zero) can be generated in this manner. These pumps generate a waste stream of liquid that must be properly disposed of. The waste stream can be reduced by recycling the liquid; however, a cooling system for the liquid stream may be required to avoid overheating the pump.

*b. Design criteria.*

(1) Typically, the airflow rate is specified and the vacuum level is determined based on pneumatic calculations (see paragraph 5-4b). Based on conservation of energy, once flow rate and pressure are specified the horsepower requirement becomes a dependent variable and cannot be uniquely specified.

(2) Frequently, the designer will specify a flow rate and vacuum level and then select a motor based on vendor-supplied blower curves. However, it is possible to predict the required power as follows:

$$\text{power (watts)} = [\text{mass flow rate (kg/s)}] \times (g = 9.81 \text{ m/s}^2) \times [\text{change in head (m)}] / \text{efficiency} \quad (5-16a)$$

or

$$\text{power (hp)} = [\text{mass flow rate (lb/s)}] \times [\text{change in head (ft)}] / ([\text{efficiency} \times 550 \text{ ft} \cdot \text{lb/sec} \cdot \text{hp}]) \quad (5-16b)$$

(3) The efficiency term must account for both the power loss within the blower due to mechanical and pneumatic friction and the motor efficiency at converting electrical energy to mechanical energy. The change in head across the blower is calculated by using Bernoulli's equation.

**Example - Blower Selection**

Select an SVE blower to operate at a flow rate range of 142 to 189 L/s and a vacuum level of 56 mm Hg. The vapors may contain up to 500 ppm of trichloroethylene.

To meet these requirements a regenerative blower with the following performance curve was selected:

|              |      |      |      |      |      |      |      |      |
|--------------|------|------|------|------|------|------|------|------|
| Flow (L/s)   | 94.4 | 118  | 142  | 165  | 189  | 212  | 235  |      |
| Vac. (mm Hg) |      | 82.1 | 76.5 | 70.9 | 65.3 | 57.8 | 50.4 | 41.0 |

Notice that this blower can provide 189 L/s at 57.8 mm Hg. Use a spark-proof aluminum housing and seals and gaskets made of viton to be compatible with trichloroethylene.

According to manufacturer's information the blower is equipped with a 7.46-kW (10 hp) Class 1, Group D motor. A 220-volt/3-phase power supply was available at the site. Based on the power requirements, the site power, and data supplied on a motor wiring chart, 28 full load amps (FLA), an 80-amp fuse or a 50-amp breaker are required. The chart also specifies using a minimum of 8 gauge wire and thermal overload protection. Based on manufacturer's information, the maximum noise level is 81 db at 60 hertz; therefore, provide an inlet and an outlet silencer.

(4) The power loss within the blower causes a temperature rise in the air stream. The goal of the engineer in specifying a blower (or pump) is often to select a blower that is the most efficient within the desired operating range of flows and pressures, thereby minimizing power loss. This is often a difficult task for SVE/BV systems given the uncertainty associated with predictions of subsurface airflow.

(5) At the beginning of the 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 BV replaces SVE (see paragraph 5-2a.) To create flexibility, 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 not be adequate. For example, the efficiency of rotary lobe blower decreases with changes in speed. SVE/BV systems should also have ambient air intake valves which (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 the blower and maintains the blower within the proper operating range. However, the power requirements are not reduced as soil vapor flow rate is reduced, and contaminant concentrations in the offgas are reduced, decreasing offgas treatment efficiency. In situations such as this, reducing the blower size may be advisable to minimize the intake of ambient air and to maximize system efficiency.

(6) Blowers and other electrical motor driven equipment (including wiring) must be designed and constructed in accordance with National Fire Protection Association (NFPA) 70, with proper consideration given to environmental conditions such as moisture, dirt, corrosive agents, and hazardous area classification. If flammable organic vapors may potentially flow through the blower, then the designer must ensure that the blower internals are constructed of non-sparking materials; also placement of flame arrestors in piping, near the blower, should be factored into the design.

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*c. Tanks and vessels. Pressure vessels and storage tanks must be designed, constructed, tested, certified, and inspected as noted below:*

(1) Atmospheric tanks must be designed to operate at pressures from atmospheric to 3.5 kPa (0.5 psi).

(2) Petroleum, hydrocarbon, or flammable product tanks, as part of the implementation of an SVE/BV system, may be needed to store flammable products. There are some systems, such as those with liquid-phase carbon and onsite carbon regeneration, which recover pure product from the vapor stream. The thermal treatment of offgases often utilizes a fuel source, such as propane, which must be stored onsite. Also, some SVE/BV projects may have an associated groundwater and/or free-product extraction component; thus, free-product would be recovered directly from the subsurface.

(3) The tanks for storage of hydrocarbon products, especially flammable products, need to be designed, installed, and specified in accordance with NFPA Standards. Product storage tanks must include secondary containment with the capacity to contain in excess of the tank volume. Product storage tanks must also be equipped with double-walled piping (if piping is buried), vents, level switches and indicators, overflow alarms, and fire extinguishers. In accordance with Federal and local fire codes, tanks containing flammable products must be located at prescribed distances from buildings, property lines, and sources of ignition.

(4) Storage tanks for SVE/BV systems are most frequently aboveground storage tanks. If below-ground tanks are employed, the tanks must be double-walled and include leak detection. 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

(5) Tanks storing in excess of 11,000 liters of VOCs are not recommended, but if necessary, must be designed in accordance with 40 CFR, Part 60.

(6) Low pressure tanks (3.5-103.5 kPa or 0.5-15 psi) are designed to operate at pressures above 3.5 kPa (0.5 psi) but at less than pressures specified in the ASME Boiler and Pressure Code, Section VIII, Division 1.

*d. Structural design considerations.* When determining the design load for a foundation, consider the stability factor and the results of the soil report in the analysis. Consider uplift, dead loads, live loads, wind, seismic, snow, thermal, crane, hoist, vehicle, and operating loads. Foundation design requires the consideration of underlying soil stability conditions.

Wind loads: 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 forces.

### 5-11. Instrumentation and Process Controls

In the design of an SVE/BV system, a good deal of attention must be paid to the instrumentation and control system. A good instrumentation and control system design will assure that the individual components are coordinated and operate effectively. This section will present the instrumentation and control elements used in an SVE/BV design, different degrees of automation, a list of minimal acceptable components, and a description of special instrumentation that may be used in SVE/BV systems.

*a. Description of design elements.* A full SVE/BV design will include, at a minimum, the following elements:

(1) P&I diagrams. Piping and instrumentation diagrams show the interrelationship between process components, piping and process control devices. ISA and ANSI standards (ANSI/ISA-S5.1) govern the preparation of P&I diagrams. These diagrams show all major process components organized according to process flow. The instrumentation symbols are shown in "bubbles."

(2) Electrical wiring diagram. This diagram shows the wiring of all physical electrical devices, such as transformers, motors and lights. If appropriate, the diagram is organized in ladder logic form. See Figure 5-28 for an example.

(3) Description of components. The specifications must include a description of instrumentation and control components including installation and mounting requirements.

(4) Sequence of control. The sequence of control must be included in both the design submittal and the operation and maintenance manual. Control information concerning system start-up, system shutdown, and response to malfunctions must be included.

(5) Control panel layout. A control panel layout must be designed. This drawing will show, to scale, all electrical components and the associated wiring. Depending on the project, this control item may be submitted as a shop drawing by the instrumentation and control contractor.

(6) Logic diagram. A logic diagram must be included if the process control logic is not apparent from the P&I diagram. This diagram shows the logical (and, or, nor, if-then) relationships between control components but does not show interconnecting process flow. For example, the diagram may show that if switch #2 is placed in the on position and there are no alarm conditions, then the blower will turn on and activate a green indicator light.

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(7) Legend and standard symbols. The set of documents must have a legend to explain the symbols that are used. Regardless of the existence of the legend, standard symbols must be used wherever applicable.

*b. Degrees of automation.* The degree of automation is generally dependent on the complexity of the treatment system, the remoteness of the site, and monitoring and control requirements. Typically, there is a trade-off between the initial capital cost of the instrumentation and control equipment, and the labor cost savings in system operation. Providing automated instrumentation and control systems can reduce the time an operator needs to be on site and, therefore, operations cost. A cost / benefit analysis should be performed to determine the degree of automation. Relatively high labor costs and a short payback period can often be used to justify some level of automation. Some degree of automation is generally recommended for systems anticipated to remain in operation for more than 12 months. For SVE/BV systems, the four major operational parameters that require control are:

- Liquid collection. The condensate collection system accumulates liquid that may overflow. Liquid level indicators, switches, and alarms are required.
- Pressure/vacuum. Blowers may require vacuum breaking controls to protect the motor units. The system may also require pressure relief valves to protect tanks or vessels.
- Flow rate. Flow rate monitoring is essential to judge the progress of the SVE/BV remediation effort. Flow control is required to balance multi- well systems.
- Temperature. Temperature control may be necessary to prevent motor overload on pumps and blower, prevent carbon bed fires, or safely operate catalytic or thermal oxidation systems.

(1) Generally, there are three forms of process control: local control, centralized control, and remote control. In a local control system, all control elements (i.e., indicators, switches, relays, and motor starters) are located adjacent to the associated equipment. In a centralized control system, the control elements are mounted in a single location. These systems may include a hard-wired control panel, a programmable logic controller (PLC), or a computer. Remote control can be accomplished several ways including by means of modems or radio telemetry.

(2) To select the appropriate control scheme, the advantages and disadvantages of each control scheme must be considered. A localized control system is less complex, less expensive, and easier to construct. For example, if a level switch in a tank is controlling an adjacent discharge pump, it would obviously be simpler to wire from the tank directly to the adjacent pump than to wire from the tank to the centralized control panel and then from the panel back to the pump. As the control system becomes more complex, it becomes more advantageous to locate the control components in a central location. Centralized control systems are also easier to operate. Centralized data acquisition and control may include the use of computers or PLCs. Automated process control is a complex topic that is beyond the scope of this manual; however, several points are worth considering. The greater the number of control inputs, the more worthwhile it is to utilize computer or PLC control. For SVE/BV systems, the inputs may include signals from level indicators, flow meters, pressure switches, or thermocouples. The threshold for utilizing PLCs or computers is generally between five and ten inputs, depending on the type of input and operator background. Often plant operators will be more familiar with traditional hard-wired control logic than with control logic contained in software. However, process logic that is contained in software is easier to

change (once you learn the software) than hard-wiring. Therefore, if extensive future modifications to the proposed system may be anticipated, hard-wiring the process logic should be avoided.

(3) Modems and radio telemetry can be used to control these systems remotely. Radio telemetry is typically used over shorter distances when radio transmission is possible. Modems are used with computerized control systems. Systems can include automatic control, shutdown sequences, and a telephone dialing and reporting system that will call operators when systems reach critical points or shutdown. In addition to basic control devices, sophisticated systems that allow for remote collection of performance data are available. The process control industry has adopted the term, supervisory control and data acquisition (SCADA), to describe a collection of computer, communications equipment, sensors and other devices that interface for remote monitoring and control of complex treatment systems. Once again, considerations such as site location, capital cost, standardization, operator background, and system complexity govern the selection of these devices.

*c. Minimum acceptable process control components.* 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 percent.
- For catalytic or thermal oxidizers,
  - Automatic burner shutoff
  - Temperature monitoring and control
  - Interlock with SVE control system
- UL listed burners and fuel train

*d. Special instrumentation.* There are several specific instruments that are common to SVE/BV systems that should be considered in the design. These instruments include oxygen / carbon dioxide meters, explosimeters, organic vapor analyzers, and process gas chromatographs (GCs).

(1) Oxygen / carbon dioxide meters. Used to monitor oxygen and/or carbon dioxide levels of soil gas withdrawn from vadose zone monitoring points, as an indicator of microbial respiration (see Chapter 3). Oxygen data is especially important for determining if air is being adequately distributed through areas of

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concern during BV. Can also be used to monitor oxygen and/or carbon dioxide levels of air withdrawn via SVE systems.

(2) Explosimeter (or combustible gas indicator). May be used on sites where high VOC levels cause a potential explosion hazard. These meters must be equipped with relays to automatically shut off process component or dilute the air stream with ambient air. Catalytic combustion is the detection principle for most of these devices. Explosimeters should not be used unless oxygen monitoring is also being performed. Explosimeters can produce false readings if the level of oxygen falls below the minimum level required for the instrument to function properly. Organic vapor analyzers (e.g., FIDs), calibrated to the proper hydrocarbon component can also be used to determine if vapor levels are approaching the LEL; and do not require concomitant oxygen monitoring.

(3) Organic vapor analyzers. Can be used to monitor vapor phase VOC discharges. Units with flame ionization, photo-ionization, thermal conductivity, electron capture, or infrared detectors are typically employed (i.e., FID, PID, TCD, ECD or IR), depending on the compounds of interest. Process units (as opposed to the handheld units frequently used for environmental work) can be rack or panel mounted and equipped with control relays.

(4) Process GC. Some SVE/BV systems utilize GC-FID for onsite monitoring and control. Several vendors manufacture GCs that can be automated for process monitoring and control; however, laboratory facilities (to prepare standards, etc.) and trained chemists are also required for GC monitoring.

## **5-12. Electrical Systems Planning**

This section establishes the basic requirements for materials, equipment, and installation for electrical systems. The need for electrical systems planning must be recognized. All basic considerations that will affect the overall design must be reviewed at the beginning of the design phase. The electrical systems planning should include any future power needs that might be anticipated. The design philosophy must emphasize the following in addition to technical and statutory needs:

- Safety of personnel and equipment.
- Flexibility for expansion.
- Accessibility for operational and maintenance needs.

*a. Codes, standards, and specifications.* The following is a list of applicable reference codes, standards, and specifications. The latest revisions shall be used.

### **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

**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)**

- C.2 National Electrical Safety Code
- 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

*b. Area classifications.*

(1) Classifications.

(a) The electrical equipment shall be selected and installed in accordance with the requirements of the classifications of the various areas involved in the SVE/BV system.

(b) The areas to be classified fall into one of the following types as established for electrical installations in the National Electric Code (NEC):

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

(2) Definition of areas.

(a) All control rooms, battery rooms, and switch houses shall be designed as unclassified areas, although battery rooms require venting to prevent hydrogen gas buildup above the LEL. Where these rooms are located within or adjacent to a hazardous location (i.e., an area that may potentially have an

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explosive atmosphere) 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.

(b) 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 will 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 will be installed between adjacent fire zones where assurance of a positive differential pressure between fire zones with different classifications is required.

(c) 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.

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

(3) Application of area classification.

(a) Hazardous locations exist in many areas of a facility where flammable liquids or gases are processed. It is important that all of these locations be identified and equipped with appropriate electrical equipment to ensure safety of personnel and the facilities. There are three basic questions to be answered in classifying a location:

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

(b) 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.

(c) The likelihood of a release of sufficient quantity of flammable substances to form an explosive mixture depends upon the equipment, containers, and/or piping system containing the gas or liquids. It depends upon the presence of valves, compressors, pumps, or meters that could possibly leak. It also depends upon the ventilation available to carry the gas or vapors away.

(d) 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.

(4) Adequate ventilation. For the purposes of area classification as outlined in this practice, the definition of "adequate ventilation" is established as follows:

(a) Open structures: An adequately ventilated location is any building, room, or space which 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 (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). API RP500B considers a mechanical ventilation system capable of providing a minimum of twelve air changes per hour in all parts of the process area as adequate and as having met the intent of the NFPA Code.

(5) 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?

(6) 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 adequately 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?

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(7) 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.

(8) All area classification tasks should consider long-term planning such as future changes/modifications that may be made on the system being designated.

(9) Unclassified locations.

(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 which 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.

(10) Electrical conduits. The configuration of the electrical system will be site-specific, but some general guidelines can be followed.

- Electrical duct runs shall be designed by electrical engineers and reviewed by civil engineers for structural competence.
- Buried ducts may be installed in trenches or on fill. Permanent ducts will use concrete encasement.
- Trenching and backfilling procedures shall conform to standards provided by a civil engineer. Selected backfill shall be placed to a height above the top of the duct that will prevent damage from traffic or other surface loading.
- Existing overhead power lines should be of concern during the design phase of the project. Power lines may obstruct or create hazards during the installation of wells, equipment, and buildings.

(11) Lighting.

(a) Lighting fixtures shall be arranged, maintaining required space-to-height ratio, for even lighting and minimum glare. Lighting specifications will also be based on electrical area classification (i.e. explosion-proof systems may be required).

(b) Emergency lighting should be provided for all egress points and critical areas in the event of a power failure.

(12)Motors.

(a) Motors shall conform to the latest applicable requirements of NFPA National Electrical Code (NEC) and NEMA. Motor enclosures are specified for the area in question. Open drip-proof (OPD) motors are not usually used for SVE/BV systems. Outdoor SVE/BV systems require weatherproof motors. As a minimum, totally enclosed, fan-cooled (TEFC) motors are used. The classification of the area will determine the need for explosion-proof motors. It is only motors with a totally-enclosed-explosion-proof (TEXP) rating that are rated for both outdoor and explosive atmospheres. Motor with only an explosion-proof (X-P) rating require appropriate cover when being used outdoors.

(b) In hazardous areas, motors shall be temperature rated "T2C" where the "T" rating is as defined per Table 500-2C of the NEC (NFPA 70). Refer to NFPA 497M - 1983 for temperature requirements for motors. If the hazardous products differ from the above, a more restrictive "T" rating may be required.

(13) System voltage. Unless otherwise specified, electrical equipment shall be designed for operation at the utilization voltage listed in Table 5-3.

(14) Packaged equipment. Several items may be purchased as packaged equipment completely engineered and fabricated by the supplier. Such items may require electrical supplies and interface, or tie-ins, with other systems. Electrical distribution and control system drawings shall show all these requirements as subsystems with references to supplier's detailed drawings. Design, inspection, and acceptance of packaged equipment shall be approved by a recognized approval authority such as Underwriters Laboratories or Factory Mutual.

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(15) Heat tracing system.

(a) Electrical heat tracing shall be provided for pipes and equipment where close temperature control is necessary and as required for process and operational needs. All electric heat tracing equipment and accessories must be approved by a recognized approval authority such as Underwriters Laboratories or Factory Mutual. Impedance-type heat tracing is not acceptable. Electrical heat tracing must consider the area classification (e.g., Class I Division 2).

(b) Design, engineering, and installation criteria shall be per information detailed in NFPA NEC Article 427.

(c) The presence of electrically heated pipelines and/or vessels shall be made evident by the posting of appropriate caution signs or markings on pipelines approximately 3 meters apart on alternating sides of the pipe.

(16) Fire protection.

(a) The installation shall consist of process and utility units that are subdivided into fire zones. The delineation and classification of fire zones in all units shall comply with the provisions of the NEC (NFPA 70).

**Table 5-3  
Utilization Voltages**

| Service  | Utilization Voltage               | System Nominal Voltage |
|--|-----------------------------------|------------------------|
| Motors below<br>½ HP   | 115 v, 1-Phase, 60 Hz             | 120 v                  |
|  | 208 v, 1-Phase, 60 Hz             | 240 v                  |
| Motors<br>½ HP to 200 HP   | 460 v, 3-Phase, 60 Hz             | 480 v                  |
|  | 230 v, 3-Phase, 60 Hz             | 240 v                  |
|  | 200 v, 3-Phase, 60 Hz             | 208 v                  |
| Lighting   | 115/200 v, 3-phase, 60 Hz, 4-wire | 120/208 v              |
|  | 460 v, 3-phase, 60 Hz, 3-wire     | 480 v                  |
|  | 460/265 v, 3-phase, 60 Hz, 4-wire | 480/277 v              |
| Noncritical instruments; power and control;<br>telephone equipment | 115 v, 1-phase, 60 Hz             | 120 v                  |
| Telecommunication equipment  | 48 v DC                           | -                      |
| Shutdown systems, alarms,<br>instrumentation                       | 24 v DC<br>with battery backup    | -                      |
| Critical loads that do not<br>permit interrupt                     | 120 v, 1-phase, 60 Hz             | -                      |
| Switchgear control   | 125 v DC                          | -                      |
| Heat tracing   | 265/460 v, 3-phase, 60 Hz         | 277/480 v              |
|  | 115 v, 1-phase, 60 Hz             | 120 v                  |

(b) Fire zones shall be protected by two types of detection systems:

- 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.

(c) Each fire zone shall be protected by an independently controlled ventilation system and an independently controlled fire extinguishing system approved for the specific application. The fire extinguishing system shall be designed to operate both automatically and manually.

(d) All installations shall be in compliance with NFPA Standards and the approval of local fire and electrical inspectors. No piping component that may eventually leak shall be installed above electrical equipment. Such components include screwed fittings (not seal welded), flanged joints, and any type of valve.

(e) Some permanent SVE treatment systems have installed sprinkler heads inside the carbon vessels for fire protection. A heat detector may or may not be included to activate the fire suppression system. Otherwise a fire department connection may be sufficient to allow spraying of water on the carbon.

### 5-13. Summary of Offgas Treatment Methods

*a.* Offgas treatment methods will be discussed in this section. A complete discussion of the engineering design of air emission control devices is beyond the scope of this manual and would duplicate information in other USACE documents. This section will primarily emphasize those aspects of the offgas treatment methods that will impact the overall design of the SVE system. Offgas treatment alternatives are summarized in Table 5-4.

(1) Offgas treatment methods need to be able to cope with a potentially wide range of volatile chemicals and concentrations to prevent exposure of the surrounding area to the VOC for which the SVE or BV process is designed. The initial concentrations of VOC can range from less than 100 ppmv to percent concentrations (over 10,000 ppmv), and the treatment system must operate properly for these ranges as well as those encountered near the end of the remediation process; i.e., a few ppmv. Thus a system design must consider concentrations ranging over several orders of magnitude. The consequences of the treatment process itself (e.g., oxidation) must also be considered in selecting the materials of construction. Disposal of residuals such as spent carbon must also be addressed.

(2) The following data are required by designers of offgas treatment equipment: initial and long-term concentration ranges; complete analysis of the influent gas; total flow rate range; required removal efficiency; availability of utilities; required degree of control, monitoring, and automation. Communication between the designers of the subsurface and aboveground components is essential.

*b. Brief description of technologies.* The technologies most often used for SVE offgas treatment are briefly described below.

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(1) Vapor phase carbon can remove many classes of organic compounds including aromatics, aliphatics, and halogenated hydrocarbons. Many SVE systems utilize granular activated carbon in flow-through reactors. 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) 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 canister. When the lead column is removed from service, the lag column is moved up to the lead position and the new column (or regenerated column) is installed in the lag position. The pressure / temperature ratings of the carbon vessels must exceed the anticipated operating conditions of the SVE system equipment.

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

(c) As mentioned previously, 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. The optimum sorption conditions occur when the air flowing through the carbon has a relative humidity of 40% at 27°C at a pressure near atmospheric. At a site where the extracted air is 10°C, a relatively small increase in the temperature caused by the vent blower (e.g., 5-15°C) will generally improve carbon efficiency by reducing the relative humidity, but a large temperature increase (e.g., 50°C) would impair to the carbon sorption efficiency. However, in the winter, a larger temperature increase at the same site might be desirable for more efficient sorption. A heat exchanger or chiller could be used to moderate the temperature.

(2) Activated carbon is the most widely used adsorbent material; however, other adsorbent materials include aluminosilicate crystal structures known as "zeolites", as well as synthetic polymers. Selection of an appropriate adsorbent material is primarily a function of the contaminant to be adsorbed. Non-polar or low-polar molecules with a higher molecular weight typically adsorb well to carbon, while polar molecules would be better sorbed by zeolites or specialized polymer resins. Activated carbon has the lowest initial cost. In addition, the wide range of pore sizes of activated carbon makes it useful for a wider range of contaminants than either zeolites or polymers. Conversely, the adsorption capacity of activated carbon is relatively low and can be adversely affected by the relative humidity of the gas stream. Zeolites and polymers are expensive; however, they each have much higher adsorption capacities than activated carbon. The need to replace zeolites is rare and polymer replacement occurs only slightly more often than with zeolites. These alternate sorbents are usually regenerated to recover solvents or other materials, saving on

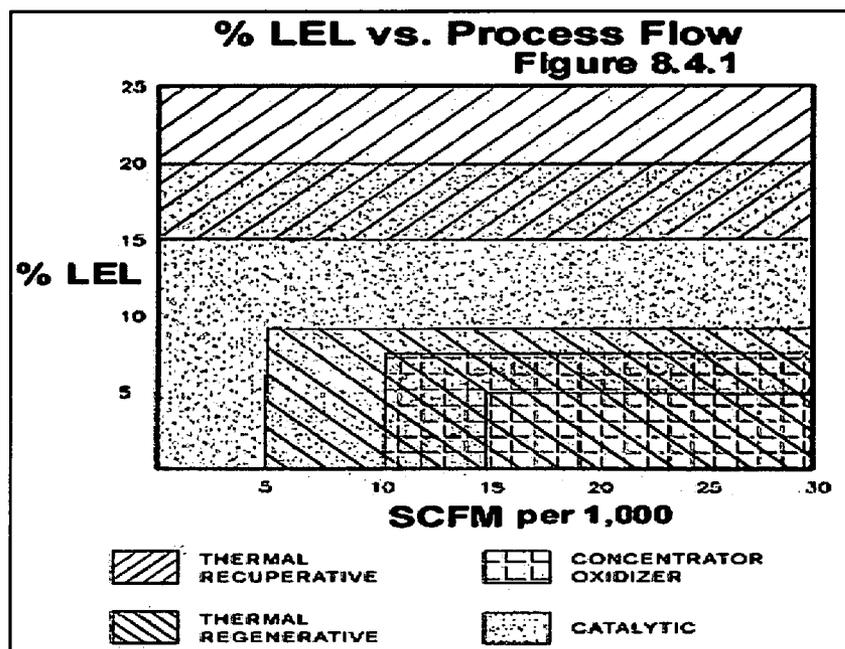
disposal costs, somewhat offsetting their high capital costs. Polymers are also hydrophobic materials and thus their adsorption capacities are substantially less affected by humidity than activated carbon.

(3) Thermal Oxidation. There are four general types of thermal oxidation systems available for controlling VOC emissions. These include: 1) Direct Flame Thermal Oxidizers (DFTO); 2) "Straight-Through" Flameless Thermal Oxidizers (FTO); (3) Regenerative Thermal Oxidizers (RTO); and, 4) Catalytic Oxidizers (Cat-ox). Each type of system operates somewhat differently, however, the primary goal of thermal oxidation is to raise the temperature of the gas stream to a sufficient level to promote oxidation (or combustion) of the contaminant to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . The heat for thermal oxidation comes from heat input to the oxidizer in the form of supplemental fuel (either gas or electric) as well as from the BTU content of the VOCs in the SVE vapor streams. In-line flame arrestors should be incorporated into the design when using thermal oxidizers. Placed just upstream of thermal oxidizers, flame arrestors can prevent fire from moving through piping, and protect other parts of the SVE system from fire or explosion. General guidelines for which type of thermal oxidation system is most appropriate for a site are provided in Figure 5-24.

(a) Significant cost savings can be realized by utilizing heat recovery techniques. Some thermal oxidation systems are "recuperative", using a heat exchanger to capture a portion of the heat of combustion and preheat the influent stream prior to oxidation in the combustion chamber. Recuperative systems can recover up to 70% of the heat of the oxidizer effluent (USEPA, 1995c), and therefore require substantially less supplemental fuel to operate. Primary heat recovery exchanges heat from the air exiting the combustion chamber with the air entering the combustion chamber. Secondary 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.

(b) Thermal oxidizers are capable of treating waste streams with virtually any VOC concentration assuming stoichiometric or excess oxygen levels are present. However, they are generally designed to treat a specific waste stream with a specific mass loading (i.e. mass of contaminant per unit of time). Variations in the mass loading due to changes in concentration require variations in the amount of auxiliary fuel (or dilution air if mixture is too rich) added to the oxidizer, but do not substantially affect the degree of treatment.

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**Figure 5-24. Applicability of thermal oxidation systems based on percent LEL influent concentration and process flow rate (from Rafson, 1998).**

(c) Catalytic oxidation is the most common means of thermal offgas treatment for SVE systems. The catalyst lowers the activation energy of the oxidation reaction allowing it to proceed at a lower temperature, usually between 300 and 900 °F. The lower combustion temperature results in significant energy savings. Catalyst manufacturers typically claim 95 percent or greater conversion of non-methane hydrocarbons. The most common catalysts for VOC oxidation are precious metals, usually either platinum or palladium supported on ceramic or stainless steel monoliths (honeycombs). Metal oxide catalysts such as chromium oxide, aluminum oxide, copper oxide and manganese oxide can be used to effectively treat chlorinated VOC (CVOC) vapors (USEPA, 1995c). Catalytic oxidation of CVOCs has become well established in the past couple of years and several vendors are offering this as off-the-shelf technology. The treatment of fluorinated compounds (e.g. freons) is more challenging, but can also be achieved although the catalyst may need to be replaced/reactivated more frequently. A complete catalytic oxidation system may include a burner, a heat exchanger, the catalytic reactor, and a stack.

(d) 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 SVE air stream is too high. This should be considered at sites where the vapor levels exceed 10 percent of the lower explosive limit. Under favorable conditions, catalysts need to be replaced approximately every three years.

(e) Catalytic oxidation of halogenated hydrocarbons generates acidic vapors. Recent advances in catalyst technology have resulted in catalysts that are resistant to halogenated compounds. However, the acid emissions require treatment. Consequently, scrubbers are typically installed in such systems. Scrubbers are described in a later section.

(f) A common concern associated with the use of catalytic oxidation of extracted vapors containing chlorinated compounds is the potential generation of products of incomplete combustion (PICs) and/or toxic breakdown products, including chlorinated dibenzo-p-dioxins (CDD or "dioxin") and chlorinated dibenzofurans (CDF). PICs are formed during thermal oxidation when there is insufficient oxygen, temperature and mixing of the vapor stream to support complete oxidation. Most commercial incineration systems are designed to have sufficient fuel/air mixing processes and temperature so that the formation of PICs during thermal oxidation is minimized (USEPA 1997c). EPA describes two primary scenarios for the formation of CDD/CDFs during combustion processes:

1. Formation of CDD/CDFs during combustion from precursor compounds, which are chlorinated aromatic hydrocarbons having a structural resemblance to the CDD/CDF molecule.
2. Formation of CDD/CDFs in the ductwork downstream of the combustion chamber as the treated stream is cooled (referred to as "*de novo*" synthesis).

According to Alley and Associates Inc. (1998), the following additional conditions must also be present for dioxin formation:

- Temperatures between 300°F and 700°F
- The presence of particulate matter in the waste gas.

The most common precursor compounds extracted by SVE systems are chlorobenzenes and chlorophenols (EPA, 1997). Because SVE produces contaminated vapors only (as opposed to combustion of solid materials), the necessary particles are not likely to be present in SVE off-gas streams as adsorption sites for the formation of CDDs and CDFs. Thus, the scenarios described above do not appear to be applicable to SVE applications. Dioxin formation has been reported on projects where catalytic oxidizers were used to treat off-gas from SVE systems. At one Superfund site, low concentrations of dioxins were reportedly generated during catalytic oxidation of an offgas stream that contained vinyl chloride as the primary contaminant. However, an equipment blank for this sampling event contained more dioxin than the offgas sample, casting doubt on the formation of dioxin.

(g) Extensive field testing for the formation of CDD and CDF from SVE thermal oxidation units has apparently not been performed. Limited CDD/CDF testing was performed on a catalytic unit being used on an SVE system at Edwards Air Force Base (EAFB), California to treat soil contaminated by petroleum hydrocarbons and CVOCs. Laboratory analysis of influent and effluent samples to the catalytic unit showed much lower CDD and CDF concentrations in the system effluent stream than in the influent stream. Ambient air samples were also obtained from locations upwind and downwind of the catalytic unit. These results revealed that the concentrations of CDDs and CDFs were much higher at the upwind location than at the downwind location (Buck 2000). Based on the results of the sampling performed at EAFB, CDD and CDF compounds do not appear to be produced from catalytic oxidation of contaminated vapors from the SVE system at this site. A collaborative review of the EAFB results was performed by Dr. B. J. Lerner, of Oakmont, PA. Based his review, Dr. Lerner concluded that the results were not unexpected due to the absence of iron oxides or fly ash in the system effluent to act as sorption sites for dioxin formation.

(h) Non-Catalytic thermal oxidation involves heating the air stream to a temperature high enough for combustion. Non-Catalytic thermal oxidizers typically operate between 1,200 and 2,000°F. They are

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generally simpler and more versatile than catalytic systems because there is no need to be concerned with compatibility of the compounds with the catalyst. For SVE applications, thermal units are generally economical for the initial stages of operation and as long as concentrations remain high, however they are less efficient as concentrations decline, because supplemental fuel is required at low concentrations. Thus in most SVE applications, thermal oxidation is not economical.

(i) The same considerations regarding the formation of dioxins apply to non-catalytic thermal oxidizers as for Cat-ox units. Though it is possible that dioxin might form as a PIC, the operating conditions of thermal oxidizers used for SVE systems are not believed to be conducive to dioxin production. At least one prominent flameless thermal oxidizer (FTO) vendor has also performed testing on its FTO system during treatment of chlorinated hydrocarbons and reports that effluent streams from its FTO system do not contain dioxins or any other significant PICs or hazardous air pollutants ([www.thermatrix.com](http://www.thermatrix.com)).

(j) The influent concentrations to thermal oxidizers are often expressed as the waste stream's BTU content or the percent of the waste stream's Lower Explosive Limit (LEL). The LEL is defined as the minimum concentration of chemical vapor in atmospheric air (i.e., 21% oxygen and at 20°C) that is sufficient to support combustion. For safety reasons, the influent concentrations should be limited to 25% of the Lower Explosive Limit (LEL). In some industrial applications, concentrations as high as 50% of the LEL are allowed where continuous LEL monitors are in place.

(4) Scrubbers would be used in an SVE system to control acid gases generated by thermal oxidation. Scrubbers reduce acid gases and particulates in an air stream by transferring these compounds to a circulating liquid stream. For acid gas control, the pH of the liquid would be subsequently neutralized. Scrubbers are available in various configurations including venturi, spray tower, packed bed, fluidized bed, and sieve tray.

(5) The above description of a furnace-style oxidation unit can be modified in the form of a flare unit or even an internal combustion engine to oxidize the hydrocarbons. 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. The flare approach is rarely used in SVE or BV 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.

**Table 5-4**  
**Comparison of VOC Control Technologies**

| Control Technology         | Applicable Concentration Range ppm | Capacity Range L/s (cfm)      | Removal Efficiency | Secondary Wastes   | Advantages   | Limitations   |
|----------------------------|------------------------------------|-------------------------------|--------------------|--|--|---|
| Thermal Oxidation          | 100-4,000                          | 94-236,000<br>(200-500,000)   | 95-99+%            | Combustion products  | Up to 95% energy recovery is possible  | Halogenated compounds may require additional control equipment downstream. Not recommended for batch operations.  |
| Catalytic Oxidation        | 100-2,000                          | 94-472,000<br>(200-100,000)   | 90-95%             | Combustion products  | Up to 70% energy recovery is possible  | Thermal efficiency suffers with swings in operating conditions. Halogenated compounds may require additional control equipment downstream. Certain compounds can poison the catalyst (lead, arsenic, chlorine, sulfur, particulate matter). |
| Condensation               | >5,000                             | 47.2-9440<br>(100-20,000)     | 50-90%             | Condensate   | Product recovery can offset annual operating costs   | Not recommended for material with boiling points <310°K. Condensers are subject to scale buildup, which can cause fouling.  |
| Carbon Absorption          | 0-5,000                            | 47.2-28,300<br>(100-60,000)   | 90-98%             | Spent carbon; collected organic  | Product recovery can offset costs. Can be used as a concentrator in conjunction with another type of control device. Works well with cyclic processes. | Relative humidity must be adjusted to <50%. Ketones and aldehydes are not efficiently adsorbed.   |
| Resins Adsorption          | 500-5,000                          | 94.4-472,000<br>(200-100,000) | 95-98%             | Wastewater; captured particulate   | Product recovery can offset annual operating costs   | May require special scrubbing liquids. Equilibrium data needed for design. Packing is subject to fouling and plugging, if particulates are in the gas stream. Scale formation from absorbent/absorber interaction can occur.                |
| Biofiltration              | 0-1,000                            | 47.2-236,000<br>(100-500,000) | 90-98%             | Spent peat or compost or soil. For pelletized packed bed biofilters, periodic cleaning generates wastewater with biosolids | Direct conversion of VOCs to carbon dioxide. Operates at ambient temperature and pressure. Low relative cost.  | Can only be applied for biodegradable VOCs. For peat or compost or soil biofilters, the contaminated air stream has to be humidified.   |
| Internal Combustion Engine | >4,000                             | 24-48<br>(50-100)             | 90-98%             | Combustion products  | Combines vacuum pump and offgas treatment.   | Requires emissions monitoring; Little additional treatment possible   |
| Flares                     | >4,000                             | 24-47,200<br>(50-100,000)     | 90-98%             | Combustion products  | Can handle very high VOC concentrations and variations in feed rate/composition.   | Substantial support equipment required; Little additional treatment possible  |

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(6) 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) are 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 installed costs but is usually more difficult to permit and operate because emission monitoring must be done on the engine exhaust, and the engine can be sensitive to abrupt changes in soil vapor conditions (especially moisture).

(7) Condensation can sometimes be considered for use if the hydrocarbons are sufficiently high-boiling to be readily condensable and are present in high concentrations. While some product recovery is possible with this approach, materials which 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.

(8) 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 SVE 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) 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 packing. Improved support media are currently being developed, for example, ceramic packing material with straight passages. Biomass periodically sloughs off from the straight passages, resulting in a self-cleaning medium.

(b) The straight passages within the support media 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).

*c. Regulatory issues.*

(1) Regulatory air emissions requirements must be considered prior to the design of the offgas control system. In some situations, air emission controls will not be necessary. Air emissions of VOCs are governed by both Federal and state regulations. Often there is a state or local limit on the concentration or total mass flow (i.e. kilograms per day) of VOC emissions. However, determining the required degree of air treatment may not be as simple as researching the applicable air discharge limit. Issues regarding media transfer and the general political climate surrounding site activities may influence the design of the offgas control system. Hazardous waste site remediation activities may be subject to more stringent requirements than other activities that result in similar emissions. For example, Massachusetts has issued a draft policy regarding offgas treatment of point-source remedial air emissions (MADEP 1993) which discusses "other considerations" on media treatment devices such as air strippers and SVE systems.

(2) Impact on cost. It should be noted that when the full cost of SVE remediation is considered, the operating cost of the offgas treatment system has significant impact on the overall cost of site remediation. Therefore, as part of the SVE design process, it is worthwhile to devote ample attention to optimizing the

offgas treatment system. This may mean developing a careful estimate of the concentrations and total mass of contaminants that may be removed from the subsurface. As discussed in paragraph 5-2a(4), vapor concentrations in the extracted offgas commonly decrease over time due to diffusion or partitioning rate limitations. With decreasing vapor concentrations, the cost of most thermal and catalytic oxidation systems increases, because more supplemental fuel is required. Increasing extraction rates of an increasingly dilute vapor stream serves only to exacerbate this problem. On some projects, a thermal or catalytic oxidation unit will only be needed temporarily. Thus there may be advantages to developing a contract that allows for temporary use of the off-gas treatment unit.

#### 5-14. Summary of Condensate Treatment and Disposal Methods

a. As discussed in paragraph 5-6, condensate is typically collected because the air stream reaches 100 percent relative humidity or because water is entrained in the vapor stream. It is generally not worthwhile to construct a full-scale water treatment system merely to treat condensate collected from an SVE/BV system. Most long-term SVE/BV systems are designed not to accumulate significant amounts of condensate.

b. *The following treatment and discharge methods should be considered:*

- Sewer discharge.
- Surface water discharge.
- Discharge to a groundwater treatment system, if one exists.
- Storage in drums and disposal as a hazardous material.
- Discharge through activated carbon.

c. The decision will be based on the availability of these options, the concentration level of contaminants, the quantity of condensate generated, and applicable regulations. For most sites, the collected liquid will generally be disposed as a waste into some offsite facility. Before this decision is reached, there may be some onsite options which should be considered:

- Is there another liquid stream of similar concentration or source into which the condensate stream can be incorporated? This minimizes the permitting and handling problems and potential delays.
- How much solids are getting into the liquid stream? The solids may inhibit the ability to process the stream.
- Is there enough liquid generated to make processing economical? If the system generates only one drum of liquid every few months, it may be easier to dispose of the drum than to process it.
- If the condensate contains two phases, can the water phase be discharged to the sewer if the organic phase is disposed of offsite?

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### 5-15. SVE/BV System Housing

Often SVE/BV systems will be housed in an existing building, a shed, or a trailer. If the intent is to locate the system in an existing building, there must be adequate space, electrical power, lighting, and ventilation for the system. A shed is typically constructed in situations where housing requirements are relatively minimal. SVE/BV systems are mounted to trailers for short-term projects and pilot studies when it is apparent that mobility is necessary. For BV systems involving air injection only, a doghouse or other small storage unit is sufficient housing for the blower unit.

*a.* There are several advantages to housing an SVE/BV system. (1) The housing protects the mechanical and electrical components from the weather. Although components may be rated as weather-proof, the system will perform more reliably and have greater longevity if protected from the weather. (2) The housing affords greater security from vandalism or unauthorized tampering. (3) A heated enclosure will reduce condensate generation and thus will also minimize the need for condensate disposal or treatment. (4) The enclosure can be designed to reduce the noise emitted from the SVE/BV system.

*b.* There are, however, several disadvantages to housing the system. (1) The enclosure adds to the cost and complexity of the project. (2) Without adequate ventilation, the enclosure could allow high concentrations of VOCs to accumulate to harmful or potentially explosive levels. (3) Space limitations may make operation and maintenance more difficult.

### 5-16. Surface Covers

*a.* A surface cover or impermeable cap serves two purposes. First, it minimizes infiltration of water from the surface. Infiltration water can fill soil pore spaces and reduce airflow, or fill the SVE/BV trenches if horizontal SVE/BV wells are installed. Second, a cap may also increase the radius of influence induced by the vacuum by altering the flow geometry and preventing short-circuiting of the air currents. Surface seals tend to prevent air from entering the subsurface from near the extraction well and force air to be drawn from a greater distance.

*b.* The most common surface cover is the use of concrete or asphalt as a cap. Many sites undergoing SVE/BV have pre-existing pavement, which may act as the surface cover. Application of a driveway sealant may be necessary to render the pavement water-resistant and to make it relatively impervious to airflow. It is important to consider that the sub-grade beneath a paved area such as a parking lot may be highly permeable sands and gravels. This high permeability layer will conduct air and eliminate the usefulness of the pavement cap. If such a sub-grade is present at a site, then it is necessary to place a barrier (e.g., using a grout or clay filled trench, similar to that shown on Figure 5-20) at the periphery of the treatment area to seal this high permeability zone from "leaking" air.

*c.* A synthetic lining, or geomembrane, is often used as a surface cover to eliminate water infiltration and short-circuiting. These membranes are available in a variety of materials, with high-density polyethylene (HDPE) being the most common. HDPE linings can be easily rolled out on the site and can be removed when the treatment is complete. Care must be taken to seal the membrane to any installations that penetrate it, such as vent wells, air piezometers, and monitoring wells. Geomembranes are generally a minimum of 20 mils or greater in thickness.

*d.* Prior to the installation of a synthetic cover, the area to be treated should be graded, smoothed, and crowned, as necessary, to eliminate any excess ponding of rainwater. If possible, the synthetic cover should then be placed over the entire contaminated area, or, in the case of a pilot study, over the expected radius of influence of the test well. Membranes are typically heat seamed. Taping, however, would be appropriate for pilot studies. Gluing is not recommended for SVE applications, because glue contains VOCs. There should be a minimum of 10 cm of overlap between sections of the surface cover. The installation procedure will vary depending on the liner used; install liners in accordance with manufacturer's recommendations. To minimize damage to the liner by personnel, equipment, or the natural elements, an appropriate (15-30 cm) thickness of fill (pulverized soil, sand, or pea gravel) can be placed over the membrane. If the membrane will be left exposed, its perimeter can be keyed into a trench and backfilled to forestall short-circuiting of air under the liner. Keying the perimeter of an exposed membrane into a trench will not, however, prevent damage to the cover. In any case, runoff water should be directed to ditches that divert the water away from the treatment area.

*e.* The ability of a surface cover to prevent short-circuiting should not be over-estimated, even if it appears to be impermeable. Beckett and Huntley (1994) examined this issue at a number of sites and concluded that surface covers do not appear to act as confining layers in most cases due to imperceptible air entry paths in the surface cover, or to highly permeable base layers directly beneath the cover. Uniform vacuums at depths suggest a good surface seal and largely horizontal flow, whereas, increasing vacuum with depth suggests communication with the surface.

#### **5-17. Design Considerations for Aboveground Soil**

Many elements of designing full-scale SVE or BV systems also apply to aboveground soil pile systems. The following summarizes full-scale design elements and considerations that are likely to be unique to this soil treatment approach. Guidance for construction of an aboveground soil pile can be found in 40 CFR 264.250, Subpart L - "Waste Piles." If a structure is to be constructed to house the soil pile, 40 CFR 264.1100, Subpart DD - "Containment Buildings," should be consulted. Figures 3-7 and 3-8 show a typical cross-section and plan view for an aboveground soil pile.

*a. Liner system.* As indicated in paragraph 3-2e, aboveground soil pile treatment systems are commonly constructed on low-permeability liners to provide water/leachate drainage control. A high-density polyethylene or other synthetic liner system is best suited to a temporary remediation system, and is not well suited for long-term or repeated usage. Synthetic liner systems are typically easy to tear. For a permanent aboveground soil-pile treatment program, a more durable base, such as a concrete pad or a compacted clay overlying a HDPE liner, should be considered for design and construction. Trenches within the pad can be used to house aeration piping and gravel, thus facilitating repeated soil removal and pile construction. The liner system should have a perimeter berm to prevent run-on water from entering the treatment system as well as to keep contaminated liquids contained. A leachate collection/drainage system should be constructed to collect irrigation liquids or precipitation. The liquids may be recirculated or treated.

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*b. Soil placement/soil pile construction.*

(1) Although overall project costs may increase due to excavation costs, construction of aboveground soil piles provides an opportunity to modify soil characteristics or facilitate the incorporation of nutrients and other amendments into impacted soils. For example, impacted soils may be processed using a mechanical shredder to eliminate clods or other heterogeneities in soil texture. Liquid nutrient applications may be made separately, or combined with the shredding operation. The addition of composting materials to impacted soils may also be considered.

(2) During aboveground soil pile construction, soil compaction should be avoided as much as possible. Use of front loaders, conveyance systems, or equivalent should be used to place soils on the lining system rather than spreading soils with grading equipment. Compaction due to equipment traffic on impacted soils will likely cause air flow anomalies such as short-circuiting, because uniform compaction in aboveground soil piles is difficult to control.

*c. Aboveground soil pile geometry.*

(1) An advantage of aboveground soil piles is that the system can be designed to conform to available space. Nevertheless, the following considerations should direct the final configuration and geometry of the soil pile:

- Total soil volume requiring treatment and available space.
- Soil permeability, and potential modifications to soil structure under consideration.
- Available equipment and construction options.
- Aesthetic considerations.

(2) As indicated in paragraph 3-2h, construction of aboveground soil piles can become complicated when the height of the biopile exceeds the reach of a front end loader (NEFSC 1996). For this reason it is recommended that biopile height not exceed 8 feet (2.4 m). The geometry of aboveground soil piles is that of a flat-topped pyramid having a trapezoidal cross-section. Side slopes are generally set at horizontal to vertical ratios of 1:1 to 1.5:1. The degree of side-sloping generally takes into consideration the physical properties of soil that are to undergo treatment, the duration of treatment, and whether the aboveground soil pile will be exposed or covered. Construction with a front end loader will limit the width of the biopile depending on the reach of the bucket and the height of the pile. Long, narrow piles are recommended to allow the front end loader to construct the pile by dumping contaminated soils onto the pile from either side down the length of the cell. This construction technique will keep the construction equipment from driving on the pile and compacting the soil.

(3) Generally it is recommended that aboveground soil piles be rectangular in plan. The maximum soil pile width is determined by the ability to maintain a uniform air flow along the entire length of the slotted vent screen installed in the soil pile. Further, the network of slotted pipes should be constructed to allow for flow adjustments within various segments of the pipe network. The proximity of slotted pipes to soil pile exterior surfaces must be inspected to assure that preferential or short-circuited air flow is not realized. Pipes can be placed in the pile by jacking, careful installation near the base during pile construction, or in trenches in the underlying pad. Battaglia and Morgan (1994) provide a theoretical and analytical overview of these design considerations.

(4) Generally, the air flow network manifold parallels the long dimension of the rectangular soil pile. In large soil volumes, air flow manifolds on two sides of a soil pile may be considered. The length of the biopile will depend on the volume of soil to be treated and the space availability at the site. While there are no restrictions on the length of biopiles, it is recommended that soil piles not exceed a volume of 500 yards. For sites with larger volumes of soil to be treated, additional cells should be constructed. Advantages of constructing discrete piles include ease of construction and maintenance, as well as providing the site manager with the ability to segregate soils that may have longer treatment times.

*d. Aboveground soil pile covers.* In comparison to other technologies addressed in this manual, design and installation of covers is unique to aboveground soil piles. Covers may be required to comply with local air pollution control district requirements to prevent volatile organic compound emissions, or to maintain favorable microclimate conditions within the soil pile. Covers can be designed to minimize stormwater infiltration into treated soils, and/or minimize/maximize thermal loss/gain. Selection of a cover should consider the candidate materials' resilience to withstand ultraviolet radiation, macroclimate conditions at the jobsite (e.g., magnitude and duration of winds), the ease of repair or replacement should tears or other mechanical damage occur, and the type of access that is necessary during system operation. If optimization of thermal gain is under consideration, clear or translucent materials are generally considered to be more effective in achieving elevated temperatures over black or opaque materials. If a geomembrane or other impermeable cover is used to cover the soil pile, a geonet drainage layers can be placed beneath the geomembrane to facilitate airflow to the entire surface area of the soil pile. Covered aboveground soil piles have often included structural supports to suspend the cover above the soil pile rather than allowing it to rest on the soil pile surface. The intent is to maintain uniform air entry into the soil pile. The advantages/disadvantages of alternative support systems are unclear. Geomembranes are somewhat difficult to work with due to their thickness. Lighter alternatives exist, including polyester-filament reinforced polyethylene sheeting. These have strength adequate to withstand wind conditions over the typical duration of biopile use.

## 5-18. Process Safety Review

*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 each unit operation and possible hazards, and operations and maintenance difficulties that might occur. All findings shall be recorded and a formal response prepared. Figure 5-25 is a sample Process Hazard Review form. The review should be held no later than 30 calendar days before the start of the SVE/BV system operation, and all deficiencies should be corrected prior to system startup.

*b. HAZOP study.* A HAZOP study is defined as the application of a formal systematic detailed examination of the process and engineering intention of new or existing facilities to assess the hazard potential of operation outside the design intention or malfunction of individual items of equipment and their 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 intention. These deviations, each of which can be associated with a word or phrase, are called "guide words" because when used in association with a design and operating intention

PROCESS HAZARD REVIEW

DATE \_\_\_\_\_

PROJECT: \_\_\_\_\_

Review NO.

GUIDE WORD/VARIABLE: \_\_\_\_\_  
e.g. Hi/Level

INTENTION/LOCATION:

CAUSE/CONSEQUENCE:

ACTION BY: \_\_\_\_\_

QUESTION OR ACTION RECOMMENDED:

RESPONSE:

Figure 5-25. Sample process hazard review (HAZOP).

they guide and stimulate creative thinking toward appropriate deviations. The following is a list of 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 effect - incorrect differential pressure - two-way flow - emergency venting - incorrect operation - in-line spare equipment.
- MORE FLOW:** Increased pumping capacity - increased suction pressure - reduced delivery head - greater fluid density - exchanger tube leaks - restriction orifice plates deleted - cross connection of systems - control faults - control valve trim changed.
- LESS FLOW:** Line restriction - filter blockage - defective pumps - fouling of vessels, valves, orifice plates - density or viscosity changes.
- MORE LEVEL:** Outlet isolated or blocked - inflow greater than outflow - control failure - faulty level measurement.
- LESS LEVEL:** Inlet flow stops - leak - outflow greater than inflow - control failure - faulty level measurement.
- MORE PRESSURE:** Surge problems - leakage from inter-connected HP system - gas breakthrough (inadequate venting) - isolation procedures for relief valves defective - thermal overpressure - positive displacement pumps - failed open PCVs - design pressures - specification of pipes, vessels, fittings, instruments.
- LESS PRESSURE:** Generation of vacuum condition - condensation - gas dissolving in liquid - restricted pump/compressor suction line - undetected leakage - vessel drainage - blockage of blanket gas reducing valve.
- MORE TEMPERATURE:** Ambient conditions - fouled or failed exchanger tubes - fire situation - cooling water failure - defective control - heater control failure - internal fires - reaction control failures - heating medium leak into process.
- LESS TEMPERATURE:** Ambient conditions - reducing pressure - fouled or failed exchanger tubes - loss of heating - depressurization of liquified gas - Joule/Thompson effect.

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|                        |  |
|------------------------|--|
| MORE VIS-<br>COSITY:   | Incorrect material specification - incorrect temperature - high solids concentration.  |
| LESS VIS-<br>COSITY:   | Incorrect material specification - incorrect temperature - solvent flushing.   |
| COMPOSITION<br>CHANGE: | Leaking isolation valves - leaking exchanger tubes - phase change - incorrect feedstock/specification - inadequate quality control - process control upset - reaction intermediates/byproducts - settling of slurries.   |
| CONTAMI-<br>NATION:    | Leaking exchanger tubes or isolation- incorrect operation of system- interconnected systems (especially services, blanket systems) - effect of corrosion - wrong additives - ingress of air shutdown and startup conditions.   |
| RELIEF:                | Relief philosophy (process/fire, etc.) - type of relief device and reliability - relief valve discharge location - pollution implications - two-phase flow - effect of debottlenecking on relief capacity.   |
| INSTRUMEN-<br>TATION:  | Control philosophy - location of instruments - response time - set points of alarms and trips - performance check points - sampling ports - time available for operator intervention - alarm and trip testing - fire protection - trip/control amplifier - panel arrangement and location - auto/manual facility and human error - fail safe philosophy; |
| SAMPLING:              | Sampling procedure - time for analysis result - calibration of automatic samplers - reliability/accuracy of representative sample - diagnosis of result.   |
| CORROSION/<br>EROSION: | Cathodic protection arrangements internal/external corrosion protection engineering -specifications - embrittlement - stress corrosion cracking - fluid velocities.  |
| SERVICE<br>FAILURE:    | Failure of instrument air/stream/nitrogen/cooling water/hydraulic power/electric power/water or other - contamination of instrument air, nitrogen, etc. - telecommunications - heating and ventilating systems - computers.  |
| ABNORMAL<br>OPERATION: | Purging - flushing - startup - normal shutdown - emergency shutdown - emergency operations.  |

|                 |  |
|-----------------|--|
| MAINTENANCE:    | Isolation philosophy - drainage - purging - cleaning - drying - blinding - access - rescue plan - training - pressure testing - work permit system - condition monitoring.   |
| IGNITION:       | Grounding arrangements - insulated vessels/equipment - low conductance fluids - splash filling of vessels - insulated strainers and valve components - dust generating and handling - hoses - hot surfaces.  |
| SPARE EQUIPMENT | Installed/non-installed spare equipment - availability of spares - modified specification - storage of spares - catalog of spares, etc. - test running of spare equipment.   |
| SAFETY:         | Toxic properties of process materials - fire and gas detection system/alarms - emergency shutdown arrangements - fire fighting response time - emergency and major emergency training - contingency plans - TLVs of process materials and methods of detection - first aid/medical resources - effluent disposal - hazards created by others (adjacent storage areas/process plant, etc.) - testing of emergency equipment - compliance with local/national regulations. |

### 5-19. Examples of SVE/BV System Designs

*a.* The major SVE/BV components have been individually discussed in paragraphs 5-3 through 5-16. This section will demonstrate, by example, the interrelationship among components. In this section, a hypothetical site will be considered and a sample preliminary SVE design will be established. Actual SVE systems can be designed in innumerable ways based on site conditions, contaminant properties and concentrations, project duration, and customer preference.

*b.* This section will acquaint the reader with design documents. See Chapter 6 for a more detailed discussion of design documents.

#### (1) Site layout.

(a) A sample site plan is shown in Figure 5-26. The site plan shows the location of major site components and helps address the following issues:

- Treatment system location.
- Well and piezometer locations.
- Location of buried piping.
- Road access.

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- Site grading for drainage.
- Electrical hook-up location.
- Gas hook-up.

(b) As discussed in paragraph 5-2, the locations of the vapor extraction wells are of great significance to the overall design, and depend on many factors including nature and extent of contamination, soil characteristics, and air permeability. In this example, the wells were placed within the zone of high contaminant concentrations to maximize removal rates. Air piezometers were located at increasing distances from the vapor extraction wells in several directions. This example illustrates that site drainage is particularly important if an impermeable liner is placed on the site as incorrect grading will cause ponding. Also, it is important to be aware of the location of utilities both for the purpose of accessing them for the treatment system and to avoid damaging them during subsurface work. Typically, the mechanical details of the treatment system are not shown on these drawings, depending on the scale of the treatment system relative to the site.

(2) Process design.

(a) A typical preliminary SVE Piping and Instrumentation (P&I) diagram is shown in Figure 5-27. In this example, soil vapor is extracted from four wells. The well layout resulted from data collection during pre-design testing and subsequent modeling of airflow streamlines to arrive at an effective radius of influence at which an acceptable velocity was predicted. In the resulting design, the flow converges at an inlet manifold where flow is controlled and pressure is monitored. The vapor stream progresses through an air/water separator, inlet filter, inlet silencer, blower, outlet silencer, and either vapor phase carbon or catalytic incineration. All these components have been described in detail in previous sections. Process controls and instrumentation, such as gauges, valves, and indicators are also shown.

(b) This sample process design demonstrates several features of typical SVE systems that may not have been emphasized in previous sections. These features include:

- Vapor sampling ports which are necessary to assess the progress of the remediation and the effectiveness of offgas treatment.
- An ambient air intake to be used during start-up, shutdown, and to dilute the air stream, if necessary.
- Temperature controls to avoid overheating the blower.

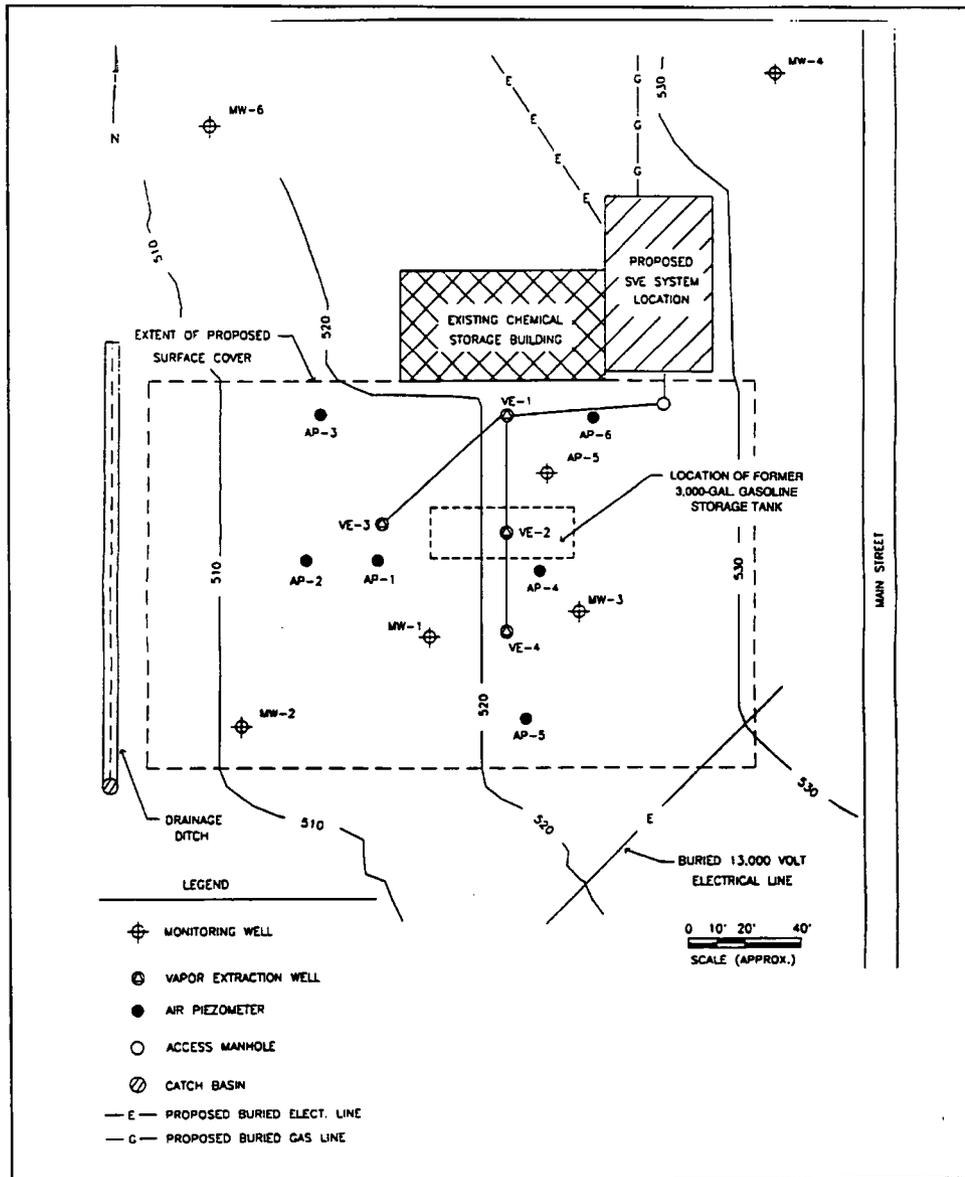
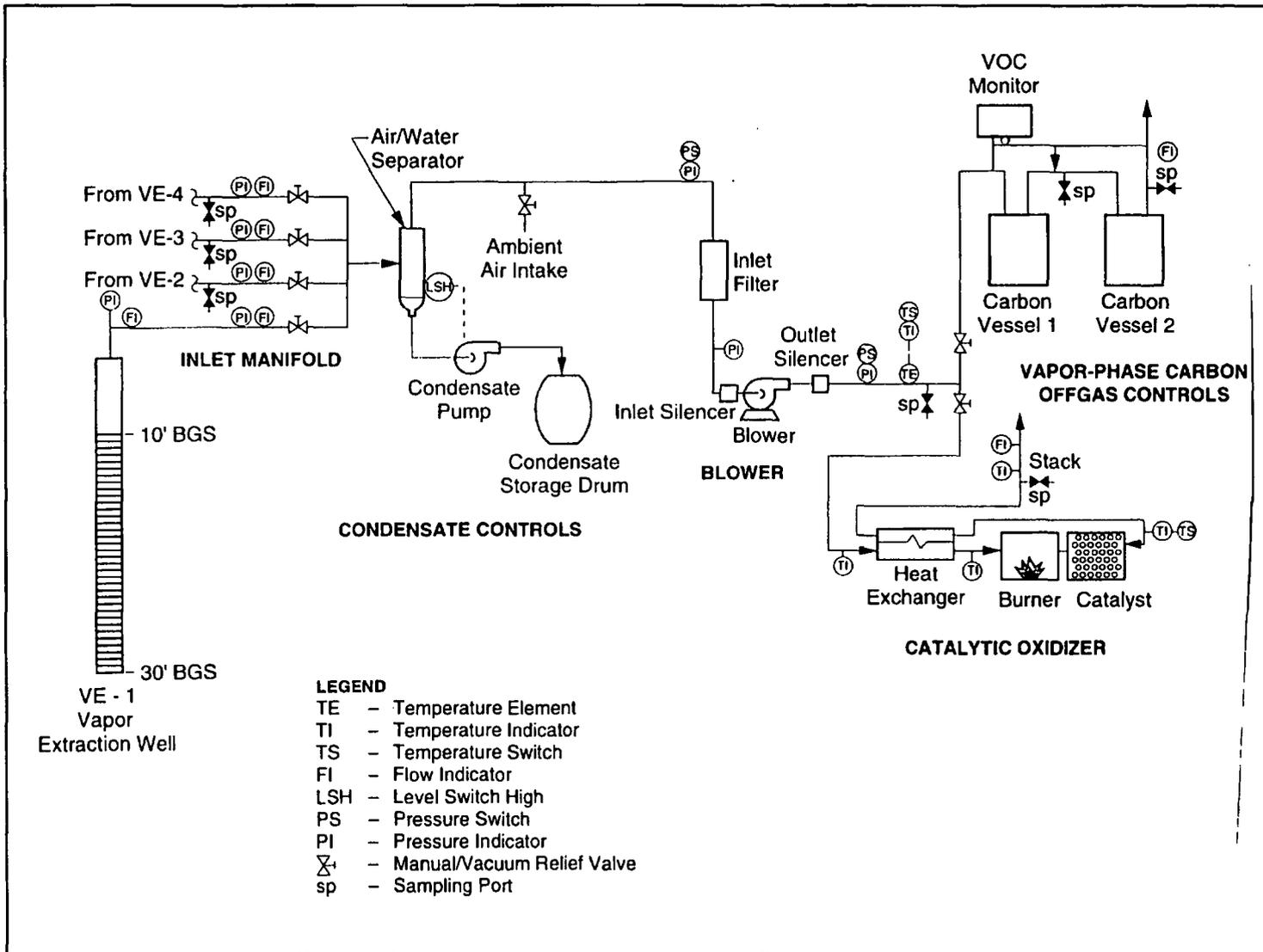


Figure 5-26. Typical SVE site plan.

Figure 5-27. Typical SVE preliminary P&I diagram.



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(c) This design shows both vapor-phase carbon and catalytic incineration mainly for illustrative purposes. However, it may not be unreasonable to include both forms of control in some situations. The contaminant concentration will decrease with time and catalytic oxidation, relative to carbon, is more cost effective for the initially concentrated vapor streams. For example, it may be economical to lease a catalytic incinerator for the first several months of a project and utilize carbon for the remainder of the project.

(3) Mechanical design.

(a) A mechanical layout shows all treatment system components drawn to scale and dimensioned. Particular detail is devoted to components requiring onsite construction and installation. Less detail is devoted to vendor-supplied components. For example, the blowers are merely drawn to the appropriate dimensions and located; complete mechanical details can be obtained from the manufacturer. To retain clarity at the scale of the drawing, all piping below a certain nominal size should be shown schematically and not drawn to scale.

(b) To minimize the distances of interconnected piping and wiring, the general layout typically follows from the Process Flow Diagram. The mechanical design must allow the components to be easily installed and maintained. System controls, particularly alarms, must be visible. For SVE systems mounted on skids or trailers, the mechanical designer must pay close attention to the weight distribution of the components.

(4) Electrical design.

(a) The electrical design must incorporate the power requirements and the process controls. The process controls shown in this example are electrical but they could also be pneumatic. Figure 5-28 illustrates a typical electrical schematic for an SVE system.

(b) In this example, a 460-volt, three-phase, three-wire hookup is supplied to the system. The blower motor and the catalyst main control panel will operate off of the 460-volt, three-phase power. The remainder of the electrical controls will operate with single-phase 115-volt power that is achieved with a transformer. This example assumes that the vendor-supplied catalytic incinerator comes complete with its own controls, and the controls would not be designed by the engineer. The 115-volt electrical controls are shown in typical ladder logic format. Notice that the blower can be shut off by any of the following three conditions: (1) high water level in the condensate tank, (2) high pressure at the blower, or (3) high temperature at the blower outlet. A separate electrical hookup is provided for the utility outlet, a fluorescent light, and the VOC meter power supply. This allows the SVE system to be shut down without impacting these components.

(c) Logic diagram. A logic diagram shall be included as part of the electrical control design, if needed for clarification.

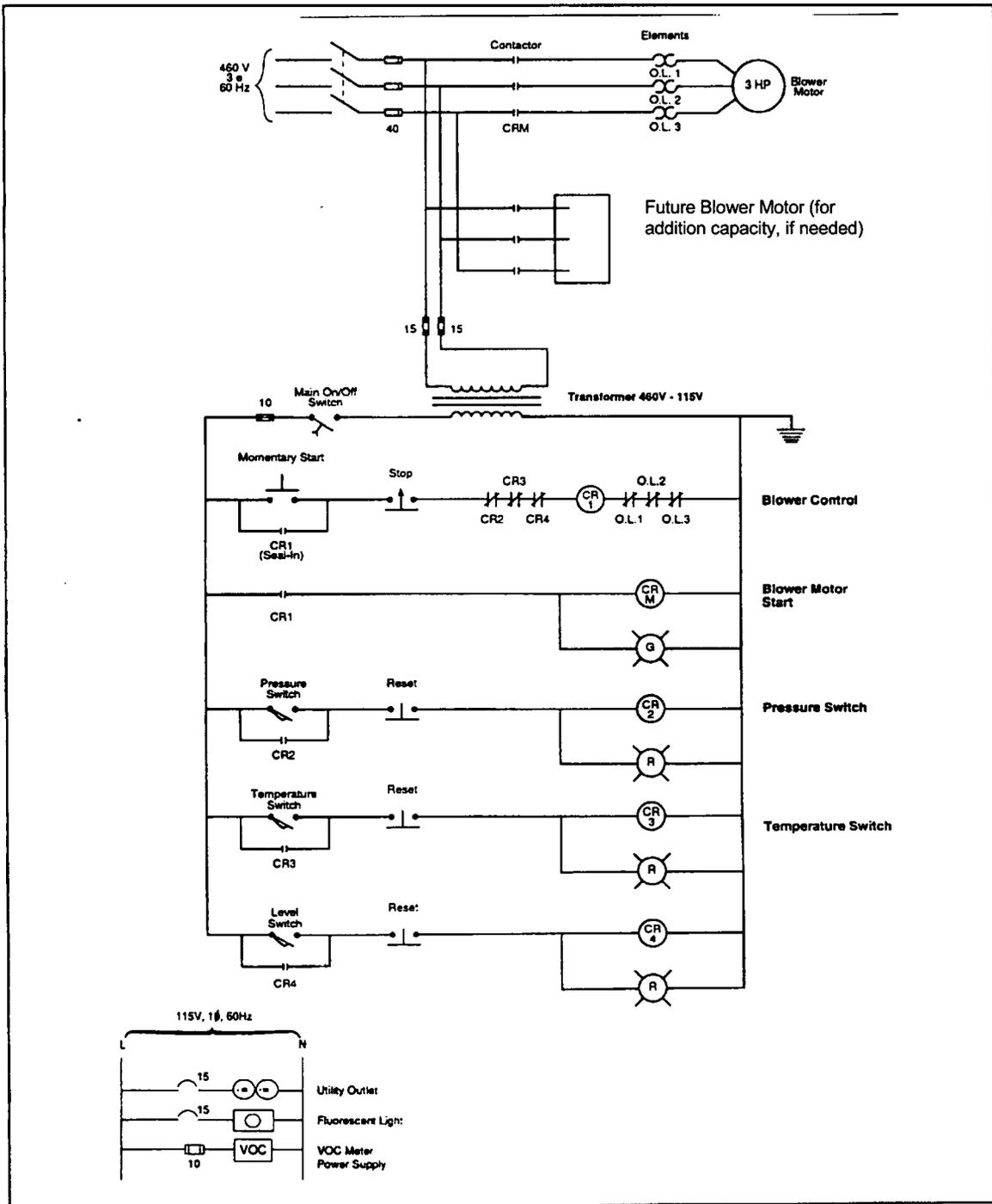


Figure 5-28. Typical SVE electrical schematic.

## Chapter 6 Documents for Design and Construction of SVE/BV Systems

### 6-1. Introduction

This chapter discusses the prescribed formats for the development of full-scale design documents for SVE/BV. The design analysis must include a complete narrative description as well as supporting calculations including the material balances and modeling assumptions and results. This information is required to be submitted as part of the design package; however, it is not required to be included as part of the construction bid package issued to contractors.

### 6-2. Applicable USACE Design Policy and Requirements

The following USACE regulations apply to the development of design documents in their various stages for the USACE:

| <u>Regulation</u> | <u>Title</u>   |
|-------------------|--|
| 1110-2-1150       | Engineering and Design for Civil Works Projects                                  |
| 1110-345-100      | Engineering and Design - Design Policy for Military Construction                 |
| 1110-345-700      | Engineering and Design - Design Analyses, Drawings, and Specifications           |
| 1165-2-132        | Hazardous, Toxic, and Radioactive Waste (HTRW) Guidance for Civil Works Projects |
| 1180-1-6          | Construction Quality Management  |

### 6-3. Design Document Components

This paragraph outlines the contents of various design packages that are typically prepared to procure SVE/BV systems. Content of the packages depends on the acquisition strategy, customer requirements, and regulator requirements. USACE-CEGS Guide Specifications for Military Construction which are typically included or can be modified for SVE/BV design are listed beneath each design component. A potential specification section shown ending in "XXX" is one for which a CEGS does not currently exist but which is under development or should be developed based on the project requirements. The designer should always check the TECHINFO web site for the most recent versions of all guide specifications and the addition of new ones.

a. *List of specification sections.*

(1) Work plans.

- 01240 Cost and Performance Report
- 01270 Measurement and Payment
- 01320 Project Schedule
- 01330 Submittal Procedures
- 01351 Safety, Health, and Emergency Response (HTRW/UST)
- 01355 Environmental Protection
- 01450 Chemical Data Quality Control
- 01451 Contractor Quality Control
- 01780 Closeout Submittals
- 01xxx Sampling, Analysis, and Disposal of Waste
- 01810 Commissioning and Demonstration for Soil Vapor Extraction (SVE) Systems
- 01830 Operation, Maintenance, and Process Monitoring for Soil Vapor Extraction (SVE) Systems

(2) Site work.

- 02111 Excavation and Handling of Contaminated Material
- 02120 Transportation and Disposal of Hazardous Materials
- 02210 Subsurface Drilling, Sampling and Testing
- 02220 Demolition
- 02230 Clearing and Grubbing
- 02260 Soil-Bentonite Slurry Trench for HTRW Projects

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- 02300 Earthwork
- 02316 Excavation, Trenching and Backfilling for Utilities Systems
- 02372 Waste Containment Geomembrane
- 02373 Separation/Filtration Geotextile
- 02374 Geosynthetic Drainage Layer
- 02570 Valve Manholes and Piping and Equipment in Valve Manholes
- 02741 Hot-Mix Asphalt (HMA) for Roads
- 02754 Concrete Pavements for Small Projects
- 02975 Sealing of Cracks in Bituminous Pavements

(3) Well specifications.

- 02522 Vapor Monitoring Wells (Ground Water Monitoring Wells Specification can be modified)
- 02521 Vapor Extraction Wells (Water Well Specification can be modified for SVE/BV wells)

(4) Treatment specifications.

For example:

- 11215 Fans/Blowers/Pumps; Off-Gas
- 11226 Vapor Phase Activated Carbon Adsorption Units
- 11378 Thermal (Catalytic) Oxidation Systems
- 11393 Filtration System
- 11500 Air Pollution Control
- 02150 Piping: Off Gas

(5) Control, instrumentation, and wiring specifications and diagrams.

11XXX Instrumentation and Controls (may be included in blower specification)

(6) Piping layout.

11XXX Piping, Valves, and Appurtenances

11XXX Condensate Control

(7) Component specifications.

15080 Thermal Insulation for Mechanical Systems (if applicable)

(8) Electrical/control specifications.

16370 Electrical Distribution System, Aerial

16375 Electrical Distribution System, Underground

16415 Electrical Work, Interior

16475 Coordinated Power System Protection

*b. Information to be included in a Request for Proposal (RFP) for services. (For a performance requirement for the entire system, including operation.)*

(1) Operating parameters, ranges, and goals.

01XXX Summary of Work (Including criteria for judging adequate performance, such as total and per-well flows, clean-up goals, monitoring requirements, etc.)

(2) Refer also to paragraph 6-3a for List of Division 1 through 16 Specifications. Note that many of these would not be applicable to a request for proposal

*c. Drawings. (Fewer drawings would be required for designs using package systems and performance-based RFPs.)*

- Site location.
- Plan and profile.

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- Well construction and surface cover details.
- Exterior details.
- Process and Instrumentation Diagram.
- Piping and equipment layout.
- Piping sections.
- Interior details.
- Power plan.
- Power/control plans.
- Electrical details.
- Lighting, power, and one-line electrical diagrams. Areas with NFPA hazard classifications that require upgraded/special electrical components should be shown on the drawings.

*d. Other typically required specifications.*

- 01500 Temporary Construction Facilities
- 13121 Metal Building Systems (Minor Requirements)
- 13405 Process Control
- 15400 Plumbing, General Purpose

**6-4. System Construction and Construction Oversight**

- a. Sequence.* Soil vapor extraction system construction includes the installation of wells, piping, above ground equipment, and controls. Installation of the wells prior to construction (or rental - see paragraph 11-4c of the above ground extraction and treatment allows the flow rate and initial vapor concentrations to be verified prior to commitment to a specific design for these costly items. Separate contracts for the wells and the above ground equipment may be desirable. To be most effective, the procurement of the aboveground equipment should lag well installation. As an alternative, the construction and operation of portions of a large system can be phased to allow for improved understanding of the subsurface performance from the early phases to better tailor the subsequent spacing of wells and sizing of aboveground equipment.

- b. *Construction Oversight.* Refer to EP 415-1-261, Volume 5, Chapter 6 for instructions on the oversight of construction of SVE (and BV) systems. That document provides additional information on submittals, materials, and execution of construction.

## Chapter 7 Commissioning and Start-up

### 7-1. Introduction

a. The objectives of the commissioning and start-up phase of a remediation system are to:

1. confirm that the system has been constructed as designed;
2. check that the equipment operates as specified;
3. facilitate making any necessary modifications in the system based on observations of site conditions that are different than expected during system installation; and
4. gather and evaluate initial operational data.

b. This chapter presents an overall strategy to follow in preparing a Start-Up Plan to carry out commissioning, shakedown, and start-up activities of an SVE or bioventing system. The system designer or operator preparing this plan is encouraged to keep in mind that each individual SVE/BV system is different and therefore may require a greater (or lesser) degree of attention than is described here for the average system. In any case, a start-up plan (or procedure) should be prepared that takes into account the system's design objectives and complexity. The plan should include:

- checklists listing each component or parameter that will be tested (samples are provided in this chapter);
- the minimum number of hours that each system, operation or parameter should be tested; and
- how each component or system should be tested (i.e., what measurements should be made).

At the end of the start-up phase, the entire SVE or bioventing system should be capable of being handed over to the owner or operator and be able to operate normally according to specifications.

c. SVE/BV systems are often implemented at sites contaminated with gasoline and diesel range hydrocarbons. In these sites especially, the Site Safety and Health Plan (SSHP) for the start-up activities must make provisions for safety monitoring relative to flammable materials. Start-up is typically the time when the highest concentrations of VOCs are present in the soil pores. These concentrated vapors may either be extracted by SVE systems or "pushed" by injection systems into adjacent areas, and may exceed the concentration deemed to be acceptable (i.e., may approach the lower explosive limit (LEL), and eventually create explosive conditions). Combustible atmospheres must not be allowed to develop or must be carefully controlled if they do exist. Flame ionization detectors (FIDs), tuned to the appropriate hydrocarbon product or component, should be employed. Combustible gas indicators (CGIs) may also be used, but only if oxygen levels are also being monitored. CGIs can produce false readings if the level of oxygen falls below the minimum level required for the instrument to function properly. For other compounds, such as nonflammable chlorinated solvents, field monitoring devices should be used to evaluate any health and safety concerns that may arise from a leak or failure during the start-up of the system. At this point in the planning process, the procurement of any required air emission or water discharge permits should be completed or underway.

## 7-2. Collection of Baseline Data

*a.* In order to evaluate the operation of the SVE/Bioventing system and the future progress of the remediation, data describing subsurface conditions collected during operation will be compared to data describing subsurface conditions before remediation began. Since the operation of the system may affect many of these conditions semi-permanently, it is critical that such baseline data be collected prior to start-up. Much of the necessary baseline data will have been collected as part of the site characterization (see Chapter 3) or during pilot testing activities needed to design the SVE/BV system (see Chapter 4). However, these data might not have been collected extensively enough across the site or recently enough to describe conditions prior to initiating remediation. Therefore, the start-up plan should begin with a review of the existing baseline site data and provision for collection of any "missing" data.

(1) To help in the evaluation, planning and gathering of baseline data, Table 7-1, Baseline Data Checklist, should be reviewed in detail. It lists the data that should be collected and analyzed before start-up of the system. As with any sampling, analysis and monitoring program, a site specific and specialized Baseline Monitoring Sampling and Analytical Plan (SAP) should be prepared that specifies:

- the type and number of samples and/or baseline parameters to be collected;
- methods of data collection;
- sample and measurement locations;
- the analytical methods; and
- QA/QC requirements.

*b.* If the remediation strategy totally or partially relies on bioventing, biological indicators such as counts of hydrocarbon-degrading bacteria, carbon dioxide and oxygen measured in subsurface probes and in extracted soil gas should be part of the SAP. To ensure project efficiency and consistency, this SAP should be prepared in a comprehensive manner so that it will also control the sampling and analyses during the start-up and operations and maintenance phases of the remediation.

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**Table 7-1**  
**Baseline Data Checklist**

| Checklist Item  | Responsible | Initials | Completion Date | Comments |
|---|-------------|----------|-----------------|----------|
| Vadose zone gaseous methane, carbon dioxide and oxygen concentration variations                           |             |          |                 |          |
| Vadose zone oxygen demand (for bioventing systems)  |             |          |                 |          |
| Vadose zone soil samples: contaminant concentrations, and moisture content                                |             |          |                 |          |
| Vadose zone soil gas VOC concentrations (SVE wells and monitoring points)                                 |             |          |                 |          |
| Bacteria enumeration in soil and/or groundwater (optional), and nutrient levels in vadose zone (optional) |             |          |                 |          |
| Groundwater levels without applied vacuum   |             |          |                 |          |
| "natural" variation (if any) soil gas pressure under different atmospheric pressure conditions            |             |          |                 |          |

Frequency and Data "quantity (how many locations, etc.)" = depends on how recently such data was collected as *part of the site investigations, site size, budget, clean-up levels, etc.*

### 7-3. Equipment Shakedown and Testing

a. *The shakedown and testing process is comprised of three primary activities:*

- Pre-commissioning check;
- Functional performance tests of individual components;
- Pre-start-up, functional performance system testing of the combined components (including actual soil vapor extraction or bioventing as warranted to test the system).

This section will discuss these closely related phases. Section 7-4 will present guidance on the actual start-up and demonstration of the operation of system(s) before handing over the system to the O&M contractor. The checklists shown in Table 7-2 and 7-3 are adapted from USACE Guide Specification 01810, Commissioning and Demonstration for Soil Vapor Extraction Systems.

(1) *Pre-commissioning checkout.* This is an inspection to verify that all the components of the system, below and aboveground, have been properly installed. A checklist for these pre-commissioning activities and functional performance component testing is presented in Table 7-2. The commissioning tests should be performed according to the agency's protocols or the system start-up plan. Any deficiencies must be corrected and retested to meet contractual or technical requirements. The pre-commissioning checklist is a working document that allows the system installer and evaluator to assess if an aspect of the system meets requirements (MR), or requires further action (AN). If further action is needed the team (or Contracting

Officer) determines what action, when it will be completed by, and who is responsible. The checklist will be initialed by the appropriate team member at completion and acceptance of a particular item.

(2) Any building foundations should be checked to verify that they were placed properly, sealed properly (if they are coated for containment reasons), and protected from damage while curing. Some equipment can be sensitive to level, particularly if it has level controls, weirs, or baffles designed to skim, separate, or otherwise control liquids in the system.

(3) The system's piping and instrumentation (P&I) diagram is the best document to use to verify that all equipment and piping are installed as designed. As-built drawings should also be created and updated as necessary. Electrical systems should be checked to verify that wiring has been completed correctly and according to the applicable code(s). The electrical One-Line Diagrams and Wiring Diagrams are good documents to use to verify electrical and instrumentation systems. Protective covers on rotating equipment should be in place. This is also the time to verify that all the required equipment specified in the SSHP, as well as equipment lockouts, safety valves and/or other pressure relief devices, and site security devices are properly installed.

*b. Functional performance tests of individual components.* The equipment functional performance tests should only commence after all the pre-commissioning checks have been performed successfully. Table 7-2 contains suggested equipment tests that should be considered for listing in a specific checklist prepared for the startup of the system. The equipment functional performance tests should be carried out in a manner to duplicate the vendor's recommended procedures. If no vendor procedures are provided, performance test methods must be developed to meet the information needs specified in the checklist. These tests should be consistent with the detailed procedures for operating all the equipment to be included either in the site-specific operating manual or the SSHP. If the aboveground system has been assembled elsewhere, some of these tests can be carried out before the system is transported and installed on-site.

*c. Pre-start-up, functional performance system testing (of the combined, above ground components).* After the pre-commissioning checks and individual component testing has been successfully completed, the testing of the entire system is performed to verify integrity prior to actual operation. The functional performance testing begins with subsystems and ends with the complete remediation system passing its performance specifications and contractual requirements testing. Any deficiencies with the system must be corrected and performance checks successfully completed before the system can be accepted.

(1) The checklist in Table 7-2 also includes the testing that needs to be done in this system performance test phase. Once the equipment and electrical systems are tested and certified ready for operation, electrical systems can be powered up in preparation for testing equipment and control systems. Analog controls are electrically tested with signal generators to verify operating ranges. Where controls provide ON/OFF signals, switches can be manually tripped to test control loops. Testing of control systems should proceed from this point to verify operability. If there are safety shutdown sequences in the control systems, they should be tested to be sure they are installed and functioning properly. Motors that can be started with hand switches should be turned on to test rotation of rotating equipment. All interlocks, motor starters controlled by interlocks or a PLC (programmable logic controller) and other relationships between equipment should be tested to determine if the responses are consistent with the design logic.

**Table 7-2  
Suggested SVE/BV Pre-Commissioning Checklist**

| Checklist Item   | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|--|-----|----|----|--------|----------|-----------------|----------|
| <b>Wells</b>   |     |    |    |        |          |                 |          |
| Wells/trenches installed per specification (depth, size, etc.)   |     |    |    |        |          |                 |          |
| Vadose and/or groundwater monitoring points installed and capped   |     |    |    |        |          |                 |          |
| Wells/monitoring points surveyed   |     |    |    |        |          |                 |          |
| Temperature, vacuum / pressure gauges installed on wellheads and monitoring points                                     |     |    |    |        |          |                 |          |
| <b>Piping Installation</b>   |     |    |    |        |          |                 |          |
| Piping and piping supports complete (including from wells/trenches)  |     |    |    |        |          |                 |          |
| Piping flushed/cleaned   |     |    |    |        |          |                 |          |
| Strainers/filters installed/cleaned  |     |    |    |        |          |                 |          |
| Valves installed and operation verified  |     |    |    |        |          |                 |          |
| Insulation/heat tape installed   |     |    |    |        |          |                 |          |
| Thermometers, sampling ports, monitoring ports and vacuum / pressure gauges installed on wells or piping               |     |    |    |        |          |                 |          |
| Pressure, vacuum or liquid leak test complete (except for joints that have to be tested while the blower is operating) |     |    |    |        |          |                 |          |

\*NA = Not Applicable

MR = Meets Requirements

AN = Action Needed

**Table 7-2**  
**Suggested SVE/BV Pre-Commissioning Checklist**

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| Checklist Item  | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|---|-----|----|----|--------|----------|-----------------|----------|
| <b>Air / Water Separator</b>  |     |    |    |        |          |                 |          |
| Leak testing complete   |     |    |    |        |          |                 |          |
| Valves installed as required  |     |    |    |        |          |                 |          |
| Operation of valves verified  |     |    |    |        |          |                 |          |
| Piping labeled and valves identified as required  |     |    |    |        |          |                 |          |
| Condensate drainage is unobstructed   |     |    |    |        |          |                 |          |
| <b>Pumps / Blowers</b>  |     |    |    |        |          |                 |          |
| Vibration isolation devices installed as specified  |     |    |    |        |          |                 |          |
| Casing and silencers undamaged  |     |    |    |        |          |                 |          |
| Where rotating equipment requires initial lubrication, check to ensure that manufacturer's procedures have been followed. |     |    |    |        |          |                 |          |
| Proper belt tension, if belt driven   |     |    |    |        |          |                 |          |
| Protective covers on rotating equipment in place  |     |    |    |        |          |                 |          |
| Manufacturer's required maintenance clearance provided  |     |    |    |        |          |                 |          |
| Pump rotation verified  |     |    |    |        |          |                 |          |
| Pressure / temperature gauges installed   |     |    |    |        |          |                 |          |
| Silencers and sound proofing installed  |     |    |    |        |          |                 |          |
| Coupling alignment/level to specifications  |     |    |    |        |          |                 |          |

**Table 7-2  
Suggested SVE/BV Pre-Commissioning Checklist**

| Checklist Item   | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|--|-----|----|----|--------|----------|-----------------|----------|
| Pipe connections installed/tested  |     |    |    |        |          |                 |          |
| Pressure / temperature gauges installed  |     |    |    |        |          |                 |          |
| Air cooling equipment properly installed, for cooling blower exhaust (if used) |     |    |    |        |          |                 |          |
| Spare inlet air filter present on-site   |     |    |    |        |          |                 |          |
| Pumps and seals intact (no leaks)  |     |    |    |        |          |                 |          |
| <b>Electrical</b>  |     |    |    |        |          |                 |          |
| Continuity checks performed to verify wiring loops.                            |     |    |    |        |          |                 |          |
| Protective covers on terminal boxes and panels in place.                       |     |    |    |        |          |                 |          |
| Power available to unit disconnect   |     |    |    |        |          |                 |          |
| Power disconnect is located within sight of the unit it controls               |     |    |    |        |          |                 |          |
| Grounding installed/checked  |     |    |    |        |          |                 |          |
| Lighting and HVAC functional   |     |    |    |        |          |                 |          |
| Lockouts on panels/switches installed  |     |    |    |        |          |                 |          |
| Wiring integrity between components and supply (no damage or deterioration)    |     |    |    |        |          |                 |          |

\*NA = Not Applicable  
 MR = Meets Requirements  
 AN = Action Needed

Table 7-2

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## Suggested SVE/BV Pre-Commissioning Checklist

| Checklist Item  | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|---|-----|----|----|--------|----------|-----------------|----------|
| <b>Instrumentation and Control</b>  |     |    |    |        |          |                 |          |
| As-build shop drawings submitted, and controls match shop drawings                  |     |    |    |        |          |                 |          |
| Panel components properly labeled   |     |    |    |        |          |                 |          |
| Control components piped or wired to each labeled terminal strip                    |     |    |    |        |          |                 |          |
| Control wiring and tubing labeled at terminations, splices, and junctions           |     |    |    |        |          |                 |          |
| Shielded wiring used on electronic sensors  |     |    |    |        |          |                 |          |
| Power connected to instrumentation  |     |    |    |        |          |                 |          |
| Valves (air bleed, dilution, and check) installed and operation verified            |     |    |    |        |          |                 |          |
| Temperature, vacuum and pressure gauges installed and calibrated over proper ranges |     |    |    |        |          |                 |          |
| Individual control, alarms and interlocks functional                                |     |    |    |        |          |                 |          |
| Instrumentation and control (PLC) system operational                                |     |    |    |        |          |                 |          |
| Telemonitoring system/modem operational   |     |    |    |        |          |                 |          |
| On-line gas analysis instruments functioning and calibrated                         |     |    |    |        |          |                 |          |
| On-line gas or liquid flow devices functioning and calibrated                       |     |    |    |        |          |                 |          |
| <b>Vapor Stream Treatment System</b>  |     |    |    |        |          |                 |          |
| Verify status of air pollution control permit (if required)                         |     |    |    |        |          |                 |          |

Table 7-2

**Suggested SVE/BV Pre-Commissioning Checklist**

| Checklist Item   | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|--|-----|----|----|--------|----------|-----------------|----------|
| Verify use of flexible lines and connectors for changing position of lead, lag, and spare activated carbon vessels (if used) |     |    |    |        |          |                 |          |
| Spare activated carbon vessel on-site, if required   |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |
| Flame arrestor properly installed on vapor oxidizer (if used)  |     |    |    |        |          |                 |          |
| Auxiliary fuel feed operational (if used)  |     |    |    |        |          |                 |          |
| <b>Ancillary Equipment</b>   |     |    |    |        |          |                 |          |
| Field monitoring instruments calibrated  |     |    |    |        |          |                 |          |
| Control panel purge system operational (if used)   |     |    |    |        |          |                 |          |
| Liquid ring fluid system functional (if needed)  |     |    |    |        |          |                 |          |

\*NA = Not Applicable

MR = Meets Requirements

AN = Action Needed

(2) Care should be taken at this point to be sure that process flow equipment (such as pumps and blowers) are only tested for short periods and not run long enough to damage the equipment running "dry". In fact, some equipment will not be able to be tested without actually extracting soil gas from the subsurface. For such equipment, short testing periods (say, up to 30 minutes) should not impact the subsurface conditions to such a degree that would invalidate the formal startup described below. After all systems have been tested and certified for operation, the entire facility should be cleaned of dirt, dust, and liquids on, under, or around the equipment. At this point, systems should be considered ready for actual operating tests (start-up).

#### **7-4. System Start-Up/Full-Scale Demonstration**

During the start-up phase, the entire remediation system is operated and remediation actually commences. The strategy for start-up is to conduct these activities sequentially, comparing observations and test data against design and performance criteria. This will allow the system to be brought on line in a systematic and safe manner to meet the operational objectives. The sequence terminates when the design and equipment performance is documented to comply with specifications, and the system is ready for transition into the operations and maintenance phase. The start-up plan may state a minimum number of operating hours with a minimal percentage downtime before the owner will accept the system.

*a.* This guidance section is divided into three sections that overlap and must be planned together: operations, subsurface monitoring, and aboveground system monitoring. Table 7-3 provides a checklist to assist in preparing a similar Functional Performance Checklist for this start-up phase. This table contains suggested equipment tests that should be considered for listing in a specific checklist prepared for the startup of the system. Data should be collected on field data collection forms as well as keeping a log of all observations. It is particularly important to note any changes that are made in the system that alter the original design or operating instructions. Individual offices should develop similar forms which meet their specific system and site needs. A few comments are in order to place the checklists in perspective:

(1) Even when a system has been designed based on a pilot test, the soil conditions at many sites may present unexpected conditions. Soil heterogeneities across the treatment area may present conditions under which a specific design point (e.g., flow rate at a specified vacuum) cannot be reached because soil conditions will not permit it (e.g., due to non-uniform soil permeability). In these cases, the pump curve for the specified equipment will need to be consulted to verify that the actual operating point is on the same curve as the design point. This may also affect air treatment equipment and flow measurement devices.

(2) Some sites which are amenable to SVE/BV treatment are relatively simple in design and hence in start-up requirements (i.e., treatment of a single contaminant in homogeneous soil with no water table impact). In this case, not all of the checklist items will be necessary, but acknowledgement using N/A will indicate that the item has at least been considered.

(3) At the very end of the start-up period, the commissioning team implements the checklists as part of a two-level start-up procedure. The team will typically consist of a member of the contracting staff; a member from the Contracting Officer's staff; the contractor, and the using entity (often from the base environmental staff). Subcontractors may be represented for specific parts of the start-up involving subcontractor equipment. The commissioning team will assign responsibilities for each of the checklist items among the team members. The checklist is a working document that allows the commissioning team to assess if an aspect of the system meets requirements (MR), or requires further action (AN). If further

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action is needed the team (or Contracting Officer) determines what action, when it will be completed by, and who is responsible. The checklist will be initialed by the appropriate team member at completion and acceptance of a particular item.

*b. Operational.* The start-up procedure will be different for each particular system configuration. In all cases, start-up of an SVE or BV system should proceed slowly with a well-planned sequence of events. This is especially important when toxic or flammable materials are to be processed through the system. All related health and safety and emergency response procedures and issues should be in place and reviewed before this phase of operation. Pieces of equipment that can be operated without process liquids or vapors should be started first. For example, sump pumps can usually be put in service independent of most other components. Where there is a need for compressed air (either utility or instrument air), an air compressor can be put in service first. Control systems must be energized before process equipment is started. Again, system configuration influence what can operate and what cannot operate without process fluids present. All equipment to be on stand-by during full operation should be started before process equipment is started.

(1) Before process systems are started, make a final check on the position of all valves and control set points. Start the SVE system without extracting soil vapor by either closing the main manifold valve to the SVE wells, by setting the pressure controls for minimum applied vacuum, and by opening the inlet bleed-valve to the ambient air. BV systems should be started with the bleed-off valves open (so air is diverted away from the injection wells). With systems using thermal oxidation, start with auxiliary fuels to heat the systems before extraction gas is introduced into the unit. Then increase the vacuum applied to the SVE wells incrementally to start extracting small flows of soil vapor and so that periodic inspection of the entire system can be made to ensure proper operation. If BV or re-injection systems are used, begin with low pressure and increase the pressure step-wise as the vacuum system flow rate is increased. Monitor the influent to an oxidation system to confirm that potentially flammable or explosive levels (15% LEL – lower explosive limit is often chosen as a cut-off point) that could damage the system are not present (most oxidation systems have self monitoring controls that prevent this from happening). Monitor the exhaust from any vapor treatment system to confirm that it is operating properly and so that emission limits are not exceeded. For BV systems, vapor monitoring may be required in nearby basements and utility corridors. Observations, sampling, and other performance testing (as described in the next two sections) can be performed during start-up to ensure that the system is operating as expected.

(2) Once the system is running at or close to the expected operating conditions, the entire system should be checked. Check the flow, pressure, and temperature at each extraction well and the operation flows, pressures, and temperatures at all monitoring points in the system (as described in the following section). Oxygen levels at monitoring points should be measured for bioventing systems. Compare operating data with equipment performance data for discrepancies. Note that systems may take time to stabilize. Some may reach equilibrium in a few minutes while others may take a day or two. The aboveground systems will reach equilibrium much more rapidly than the subsurface systems. But as subsurface systems stabilize, aboveground systems may change too.

(3) Soon after an SVE system is started, check for condensate accumulation. Check to see that the condensate removal and/or treatment systems are operating correctly. Look for evidence of condensate accumulating in piping, and check low-point drains.

(4) The sustainable discharge concentration may be manipulated to some extent by deliberately inducing airflow through the most concentrated areas of VOCs. The sustainable discharge should be maintained as high as possible balancing airflows to maximize the concentration, and/or VOC removal rates. The system balance should be checked periodically throughout the remediation program (initially every 2 weeks) to ensure that the optimum balance is re-determined, as the concentrations will change over time.

Table 7-3

Suggested SVE/BV Startup and Functional Performance Checklist

Page 1 of 4

| Checklist Item   | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|--|-----|----|----|--------|----------|-----------------|----------|
| <b>Subsurface</b>  |     |    |    |        |          |                 |          |
| SVE well specific capacity within expected ranges  |     |    |    |        |          |                 |          |
| Groundwater level rise during SVE within expected ranges   |     |    |    |        |          |                 |          |
| Vacuum levels at SVE wells and vadose zone monitoring points within expected ranges                  |     |    |    |        |          |                 |          |
| Assess adequacy of vadose zone air flow rates  |     |    |    |        |          |                 |          |
| Contaminant level at vadose zone monitoring point within expected ranges (if measured)               |     |    |    |        |          |                 |          |
| Oxygen and carbon dioxide levels at vadose zone monitoring points responding to BV / SVE as expected |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |
| <b>Piping, Valves and Instrumentation</b>  |     |    |    |        |          |                 |          |
| As wells are valved on, leak-test joints not previously tested. Repair until leaks are eliminated    |     |    |    |        |          |                 |          |
| Check for water at drainage points   |     |    |    |        |          |                 |          |
| Verify operation of heat tracing   |     |    |    |        |          |                 |          |

**Table 7-3  
Suggested SVE/BV Startup and Functional Performance Checklist**

| Checklist Item   | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|--|-----|----|----|--------|----------|-----------------|----------|
| Monitoring systems/instruments hold calibration  |     |    |    |        |          |                 |          |
| Independent measurement of air flow rates by Contractor and Testing, Adjusting, and Balancing (TAB) specialist. Results differ by no more than 10% |     |    |    |        |          |                 |          |
| <b>Air / Water Separator</b>   |     |    |    |        |          |                 |          |
| Check pressure drop across unit  |     |    |    |        |          |                 |          |
| Compare airflow rate and pressure drop against manufacturer's specifications   |     |    |    |        |          |                 |          |
| Check water level via sight glass, or other indicator  |     |    |    |        |          |                 |          |
| Check operation of condensate drain valve  |     |    |    |        |          |                 |          |
| Check setting of high-level alarm in condensate collection vessel  |     |    |    |        |          |                 |          |
| <b>Pumps / Blowers</b>   |     |    |    |        |          |                 |          |
| Start/stop functioning from all control mechanisms   |     |    |    |        |          |                 |          |
| Blower speed (rpm) meets manufacturer's specifications   |     |    |    |        |          |                 |          |
| Current draw and voltage balance match specifications for all phases   |     |    |    |        |          |                 |          |
| Temperature at inlet and outlet of unit meet manufacturer's specifications   |     |    |    |        |          |                 |          |
| Liquid ring fluid subsystem functions properly (if used)   |     |    |    |        |          |                 |          |

**Table 7-3**  
**Suggested SVE/BV Startup and Functional Performance Checklist**

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| Checklist Item   | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|--|-----|----|----|--------|----------|-----------------|----------|
| Verify operation of variable speed (if used)   |     |    |    |        |          |                 |          |
| Verify settings of vacuum relief valve, pressure relief valve, and high-temperature shutdown   |     |    |    |        |          |                 |          |
| Plot readings of pressure and airflow rate on graph, and compare to manufacturer's specifications  |     |    |    |        |          |                 |          |
| Measure noise level and note any unusual vibrations or noises  |     |    |    |        |          |                 |          |
| <b>System Controls</b>   |     |    |    |        |          |                 |          |
| Verify that controllers maintain set points by manually measuring the controlled variable with thermometer, differential pressure gauge, or other device |     |    |    |        |          |                 |          |
| Verify that interlocks function according to specifications, and in concert with other system controls   |     |    |    |        |          |                 |          |
| Verify that control system conforms to that specified in the sequence of operation   |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |
|  |     |    |    |        |          |                 |          |

\*NA = Not Applicable

MR = Meets Requirements

AN = Action Needed

Table 7-3

Suggested SVE/BV Startup and Functional Performance Checklist

| Checklist Item  | NA* | MR | AN | Action | Initials | Completion Date | Comments |
|---|-----|----|----|--------|----------|-----------------|----------|
| <b>Vapor Stream Treatment System</b>  |     |    |    |        |          |                 |          |
| Leak-test joints not previously tested. Repair until leaks are eliminated   |     |    |    |        |          |                 |          |
| Measure air flow rates at inlet and outlet  |     |    |    |        |          |                 |          |
| Measure temperature and pressure across lead and lag vessel (if used), and compare to manufacturer's specifications |     |    |    |        |          |                 |          |
| Catalytic oxidation system, and fuel feed subsystem, operate within specifications (If used)                        |     |    |    |        |          |                 |          |
| Measure organic vapor level at inlet and outlet of system   |     |    |    |        |          |                 |          |
| Soil vapor treatment system performance meets removal efficiency requirements and emission concentration limits     |     |    |    |        |          |                 |          |
|   |     |    |    |        |          |                 |          |
|   |     |    |    |        |          |                 |          |
|   |     |    |    |        |          |                 |          |
|   |     |    |    |        |          |                 |          |

\*NA = Not Applicable  
 MR = Meets Requirements  
 AN = Action Needed

*c. Monitoring of Subsurface Conditions*

Field measurements are conducted on a routine basis in order to monitor the efficiency of the SVE/BV system. Of particular concern during start-up is whether a SVE well's operating conditions are very different than those assumed during design. Many wells will be turned on for the first time during start-up, if earlier wells were pilot tested and used for design. Questions to consider include the following: Does a particular well produce the expected flow for the applied vacuum? Are vapor contaminants in the extracted soil gas at the expected concentration? Are surrounding soil gas vacuums as expected? How significantly does the applied vacuum drop in the SVE well sand or gravel pack around the well? Start-up provides the first opportunity to check design assumptions.

(1) Groundwater level measurements. Groundwater level measurements are required to evaluate the effects of the applied vacuum on water table upwelling and the subsequent effect of water table upwelling on system performance. Water table upwelling can submerge contaminated soils near the water table, rendering them inaccessible to vapor flow and therefore "unremediated". Water table upwelling also reduces the thickness of unsaturated soil near individual vents, limiting the available airflow. This usually occurs in only a localized area around each SVE well. The effects of water table upwelling can be reduced by lowering the applied vacuum, installing additional extraction vents, installing dilution air inlet vents, and/or by dewatering.

(a) The amount of water table upwelling at any point is equal to the original water table elevation plus the magnitude of the applied vacuum (in centimeters of water) (see paragraph 3-2d). Direct measurement of water table upwelling requires the wellhead to be sealed at the atmosphere to prevent loss of the applied vacuum at the time of measurement.

(b) This can be accomplished by installing a pressure transducer at a fixed elevation beneath the lowest anticipated water table within the monitoring well. The pressure transducer must be referenced to the well pressure, not atmospheric pressure, which may be greater than the air pressure in the well. Of course, care is required to ensure that no leaks are present at the measurement wellhead. Commonly, a connection with the air pressure in the well may be accomplished via an air tube built into the electrical cable. Pressure transducers of this type are usually connected to a multichannel data logger which is down-loaded at convenient intervals. Groundwater level measurement methods are also discussed in paragraph 4-5e(18).

(2) Soil vacuum or pressure measurements. Vacuum or pressure gauges installed at various locations on the SVE or BV wells, vadose zone monitoring points and the airflow manifold network are monitored during start-up so that flows and pressures can be adjusted. Johnson et al. (1990a) report that several hours to several days of system operation may be required to establish steady-state flow and vacuum conditions, depending on the air permeability of the soil. If an air permeability test has been performed prior to system design, this will have provided an indication of the amount of time needed to achieve steady-state flow. Verifying the air permeability at each extraction or injection well is also recommended. During the initial transient stage, vacuum data should be collected frequently, with the collection intervals increasing with time. For example, if electronic data loggers are used, a typical setup might collect data points every minute for the first hour, every five minutes for hours 2 through 10, every ten minutes for hours 11 through 24, and every thirty minutes thereafter. Although this should only serve as an example, the point is that the vacuum at a given radius varies logarithmically with respect to time, and as conditions approach steady-state, the vacuums will change less dramatically over a given period of time. The start-up data should be

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compared with the results of the air permeability test to determine whether any flow rate or vacuum adjustments need to be made.

(a) One of the foremost considerations stemming from vacuum/pressure data during start-up is the spatial distribution of pressure around each extraction point. This is determined by measuring the soil pressure (vacuum) in vadose zone monitoring points around and between SVE wells. The sensitivity required for vacuum (or pressure) measurements in the soil usually does not exceed 0.25 cm (0.1 inch) of water. Magnehelic® gauges or water-filled manometers can provide measurements within this general range. It is also important to evaluate whether subsurface airflow rates are adequate. Whole sets of pressure (or vacuum) data must be evaluated to assess airflow rates. Some of the questions to be answered with this data include:

- Are there locations at similar distances from SVE wells exhibiting much less influence than others?
- Are there strata exhibiting substantial differences in influence from SVE wells?
- Are these findings consistent with the conceptual understanding of the site based on existing site characterization data, or do they point to unforeseen factors?

For example, in a relatively uniform sand, one might observe the same pressure drop with distance regardless of direction, consistent with isotropic conditions.

(b) A finding, however, of little or no vacuum influence in one sector might indicate the presence of some subsurface barrier to airflow, such as a buried foundation; a utility conduit enabling air to bypass one area in favor of another; or perhaps short-circuiting of airflow due to improper installation of SVE system components. Installation of additional air piezometers might be necessary to establish the cause of such a problem. Depending on the cause, the solution could involve one or more of the following: altering the spacing or screen depth of additional extraction or injection wells; using grouting or other method to retard flow through preferential pathways; or placement of a surface cover. Accordingly, periodic adjustment of flow rates or vacuums can alleviate problems presented by stagnation zones.

(3) Soil Gas Flowrates - Soil gas flowrates must be measured in the piping from each SVE/BV well in order to balance the flow among all the wells. Without annular stabilizing fins, the non-uniform nature of airflow in pipes typically causes variations of 15% or more in airflow velocity. The data generated with Pitot tubes (differential pressure) or hot wire anemometers (heat loss) can be used to measure velocities and thereby the flow within this general range of accuracy, which is usually sufficient for balancing flows. For more accurate readings it may be necessary to measure airflow at several pre-determined locations across the pipe cross-section (i.e., transverse readings). Instruments with multiple sensing ports and averaging capabilities are also available (e.g., transverse, averaging pitot tubes). Flow monitoring ports should be positioned in straight sections of piping, according to manufacturer's directions. For example, pitot tubes should be placed at least 8.5 pipe diameters upstream, and at least 1.5 pipe diameters downstream of elbows, restrictions or other obstructions in the piping. Velocity data can be measured periodically by portable instrumentation or continuously by an electronic control system. Rotometers are sometimes used to monitor flow, but usually the large pressure drop is not considered acceptable. All these devices need to be calibrated at an established frequency.

(4) Soil Gas Contaminant Concentrations - One of the most important parameters to measure during start-up is the concentration of VOCs in the extracted soil gas, both in each SVE well and the total flow passing through the vacuum blower. Comparison of the initial contaminant level spike to subsequent

rebound spikes is a useful tool for assessing the progress of SVE operations. Also, when determining whether to continue (or shutdown) SVE operations, the rebound spike data should be included in the assessment. This early stage is when the concentrations are most close to the equilibrium concentrations between the gas, sorbed and dissolved phases. Depending on precision, accuracy, and quantification requirements, vapor concentration measurements can be performed with field instruments or laboratory analyses. Field instruments include flame ionization detectors (FIDs), photoionization detectors (PIDs), combustible gas indicators (especially applicable to free phase LNAPL situations, where very high VOC concentrations in the extracted soil gas are expected) and colorimetric detector tubes. Total VOC measurements can be acquired with FIDs or PIDs. Although PIDs respond better to halogenated and aromatic hydrocarbons, FIDs provide a good response to most types of hydrocarbon contaminants. However, FIDs are less sensitive to the moisture that is usually present in the vapor stream. Whereas FIDs and PIDs can quantify only total VOCs, individual VOCs can be measured by gas chromatography combined with the appropriate detector, such as GC/FID, GC/PID, GC/MS, etc. Compound-specific identification and quantitation can be accomplished on samples collected in the field and brought to the laboratory, by having a field lab at the site, or by using portable GC instrumentation. Portable GC instruments generally have higher detection limits than laboratory GC instruments, but provide immediate data and can be much less expensive than bringing a field lab to a site. Sampling methods and holding times are an important consideration for laboratory analyses. Samples can be collected in specially manufactured sampling bags (i.e., Tedlar), evacuated canisters, or on activated carbon or other adsorption media. When using Tedlar bags, a sampling pump will be needed to overcome the vacuum in the pipes. Analytical methods and sampling procedures should be determined by the intended use of the data and should be in accordance with the project data quality objectives. Standards used for calibration of field instruments or GCs should be representative of the approximate composition of the target VOCs. If samples are collected for laboratory analysis of individual VOCs, measurements should be taken at the same time with the field instruments so that they can become better calibrated to actual site contamination distributions.

*d. Extraction and Treatment Equipment Monitoring*

(1) Once steady-state operation is achieved, operational efficiency data should be collected. With regard to an SVE system, steady-state operation will typically mean that all systems are running without shutdowns, the vapor treatment system is working and that flowrates have basically stabilized. VOC concentrations in the extracted vapor would not be expected to be stable. This manual is not intended to describe every potential component and its associated measurement criteria. However, several major components that need to be monitored will be common to almost all SVE/BV systems, including:

- Blowers/vacuum pumps.
- Air/water separators.
- Offgas treatment systems.
- Liquid pumps.
- Analytical and/or control instruments.

(a) Vacuum pumps and blowers – operational uptime and downtime should be continuously logged if possible. Opportunities for monitoring uptime include electronic hour meters, vacuum or pressure switches, or the instrumentation and control system if one exists. The pressure and vacuum being created by the blower can be monitored by recording the value on permanently mounted pressure gauges or by utilizing pressure transducers whose signal data can be stored by a datalogger or computer system. The

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gauge pressure should be measured on both the vacuum side and pressure side of the blower because they can be used with the manufacturer's blower curve to estimate the flow through the blower. Amperage meters on the blowers can also help to estimate the flowrate and monitor the performance of the blower motor. Temperature gauges should also record the temperature of the inlet soil gas and outlet temperatures. The total extracted soil gas flowrate, the flow through the blower, the inlet bleed valve, and the vapor treatment system, (the measurement methods were discussed in the proceeding section). The VOC concentrations in the total extracted soil vapor should be monitored at a frequency that will permit (along with the flow data) the total mass of contamination removed to be calculated. VOC concentrations are most reliably measured in the pressure side of the SVE system, so that the vapor sample does not have to be collected (pumped) against a vacuum.

(b) Air/water (moisture) separators - Level meters or high and low level switches should be checked that they are operating properly so that water does not enter the blower (unless liquid ring pumps are used). Also filters should be checked frequently at startup due to the potential for dust, pipe shavings, and soil particulate to be pulled through the piping.

(c) Offgas treatment systems. - Maintaining the efficiency of the soil gas treatment system is important if air emission limits are to be continuously met. If granular activated carbon (GAC) treatment is used, concentrations should be measured in soil gas entering and exiting the units and between units if two or more vessels are used. Measurements can be made with the techniques discussed in the last section and usually consist of frequent measurements with a field instrument and periodic analysis by collecting samples for laboratory analysis. The observed mass loading rate of contaminants should be calculated to determine if the treatment system is sufficient to meet emission limits. The relative humidity of the soil gas to be treated may also need to be measured, or estimated. (As described in Chapter 5, high humidity reduces the adsorption capacity of the GAC and may need to be mitigated). The pressure drop through the GAC units should also be monitored to evaluate if the bed is becoming clogged and may need to be replaced, although this should not occur during the start-up phase. The temperature of the influent and effluent vapor streams are also important and can be used to monitor the amount of VOCs being destroyed by an thermal or catalytic oxidation system.

(d) Liquid (groundwater and or soil moisture condensate) pumps - If flows are low and condensate will be periodically removed and disposed of, the volumes can be noted in a field note book. If the condensate volume is high and is automatically pumped out and treated, a totalizer flow meter should be installed to record the total volume of groundwater/ soil vapor condensate removed. Alternatively, if an electronic pump control system is used, the flowrate information can be stored and processed. If the flowrate and contaminant concentrations in the moisture separator condensate are significant, the mass of contamination being removed may be significant enough that it should be quantified and reported as part of the remediation progress.

(e) Instrumentation and control devices should be calibrated as recommended by the manufacturer.

(2) Whether the above information is collected manually or electronically, a data management process must be established for operating components. Measurements should be made very frequently when operation begins and less frequently as the system equilibrates.

(3) It is imperative that "in-spec" and "out-of-spec" operating conditions be predetermined and listed on log sheets so that operators may detect potential problems early. It is equally important to identify

appropriate actions to be taken when "out-of-spec" conditions occur, including system shutdown, if necessary.

(4) All analytical and control instruments should be calibrated during the testing activities. Frequent checks (with results logged) and recalibrations (with results logged) of all instruments should be made during start-up to assure that proper control and analysis are occurring. This also establishes real-time reliability of the instruments.

(5) Once the initial data set is evaluated, system adjustments should be made and additional round of data collected until the system reaches a steady-state condition (as described earlier) wherein all design criteria are satisfied. At that point, start-up is complete.

### **7-5. Data Evaluation and Start-Up Report**

*a.* Depending on the complexity of the system and the extent of the start-up testing program, a status report should be submitted after each phase or at the end of the start-up testing. It should include the checklist(s), including any outstanding "Actions Needed"; all data that was collected on the operating performance of any component or system, and the results of any failed tests along with a description of the corrective action taken. Full-scale continuous operation and transfer of the system to the owner or operator shall not occur until all planned start-up activities have been performed and approved.

*b.* The start-up report should contain the following information (if collected):

- Data tables of test observations (flow readings, vacuums/pressures, concentrations, levels, etc.);
- Influences (weather conditions, mechanical or electrical problems, total operation periods and duration);
- Predicted versus actual system performance (Figure 4-17 versus 7-1) and any differences between planned performance and actual results;
- Influent and effluent discharge concentrations from the soil gas vapor treatment system (Figure 7-1);
- Problem/incident reports;
- Vapor concentrations measured in individual SVE wells or vadose zone monitoring points;
- Oxygen, carbon dioxide levels measured in vadose zone monitoring points;
- Implications of actual start-up performance on full-scale remediation schedule;
- Soil vacuum/pressure distribution shown in cross-section and in plan view;
- Applied vacuum/pressure versus flow relations for individual SVE/BV wells and/or the entire SVE/BV system;
- Liquid recovery rates from the moisture separator;
- Corrective actions that have been taken during start-up, and potential problems that may need to be addressed during the operations and maintenance period.
- For each SVE well, plots of: volume of air extracted versus time, cumulate volume of air extracted versus time, concentrations or contaminants of concern versus time, mass removal rate of contaminants of concern versus time, and cumulative mass of contaminants of concern removed versus time.

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- For the SVE system as a whole, plots of: concentrations or contaminants of concern versus time, mass removal rate of contaminants of concern versus time, and cumulative mass of contaminants of concern removed versus time.

c. Despite the available analytical and numerical models, actual vapor concentrations and recovery rates are difficult to predict prior to system operation, especially if the initial subsurface characterization was insufficient. Since these contaminant removal rates are directly related to the required treatment time, the achievable cleanup levels, and off-gas treatment requirements, actual recovery rates are a controlling factor for ultimate cleanup costs. Depending on how long the start-up period was and how much soil vapor concentration data was collected, it may be possible to get an initial indication of what can be expected by plotting extracted (individual SVE wells and/or total flow) concentrations versus time. Otherwise, this evaluation will take place during the operations and maintenance phase.

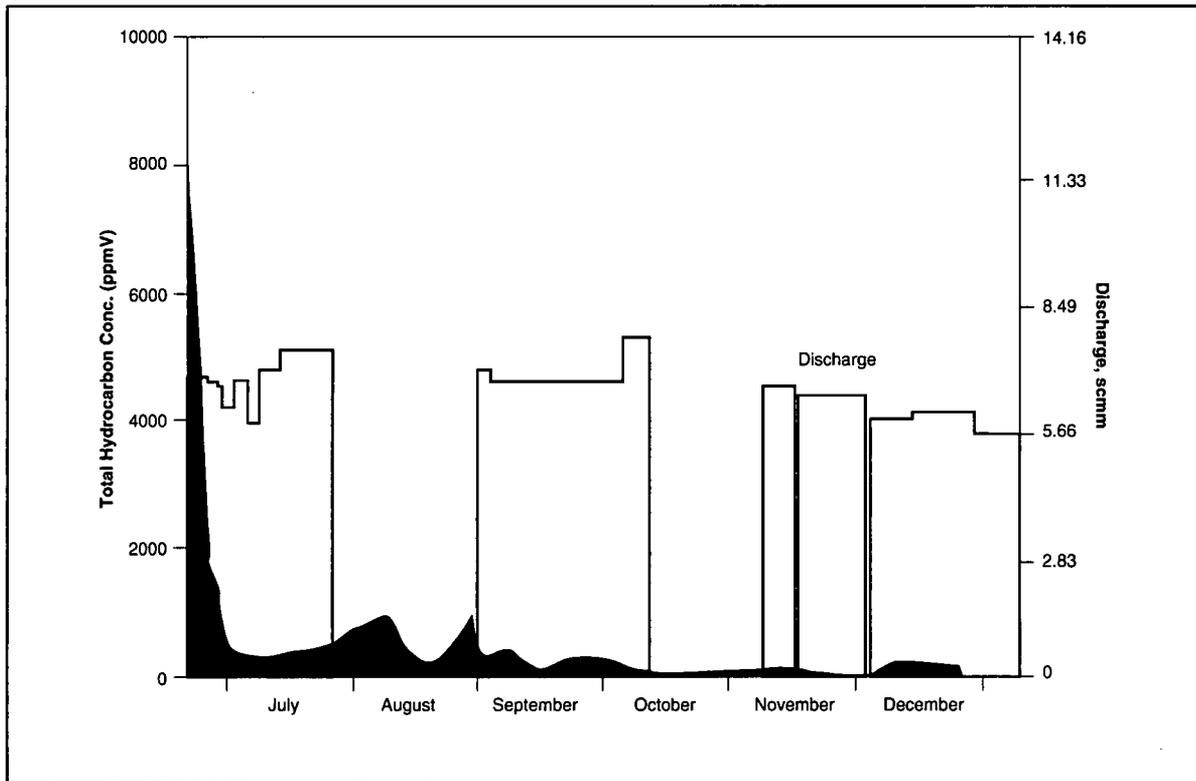


Figure 7-1. Total hydrocarbon concentration and extracted air flowrates over 6 months of SVE operation

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d. As shown in Figure 7-1 extracted concentrations typically show an initial spike in concentration, followed by a rapid decline to a sustainable contaminant concentration ranging from 1 to 10 percent of the initial concentration. In Figure 7-1, the concentrations are shown as black shading and the flow rates are shown as lines. The concentrations drop rapidly over the first few days to a more sustainable rate. (It is important to remember that, if the vapor concentration in the total flow is measured after the blower and any dilution air is being let in, these measured concentrations must be corrected to represent the overall concentration being extracted from the soil.) Except for shut-down periods, the flow rate does not change appreciably in these examples.

e. Depending on how long the start-up period was and how much soil vapor flow and concentration data was collected, calculating the mass of contamination removed may or may not be possible. However, once sustainable concentrations have been achieved (during the start-up period or later in the Operations and Maintenance phase – discussed in Chapter 8), the actual contaminant mass removal rates can be calculated as illustrated in the example in Table 7-4. Table B-1, in Appendix B, presents the molecular weights of some most common VOC compounds, a value that must be known to complete the calculation. The results of these VOC mass removal rate calculations are typically presented as contaminant removal versus time (see Figure 7-2). Cumulative mass removal should also be plotted (refer to Figure 7-3). Using estimates of the original mass of soil contaminants, the estimated treatment time can be calculated assuming a gradual decline in the actual contaminant recovery rate. The results of these calculations may also be compared with the laboratory column test results described in paragraph 4-7a.

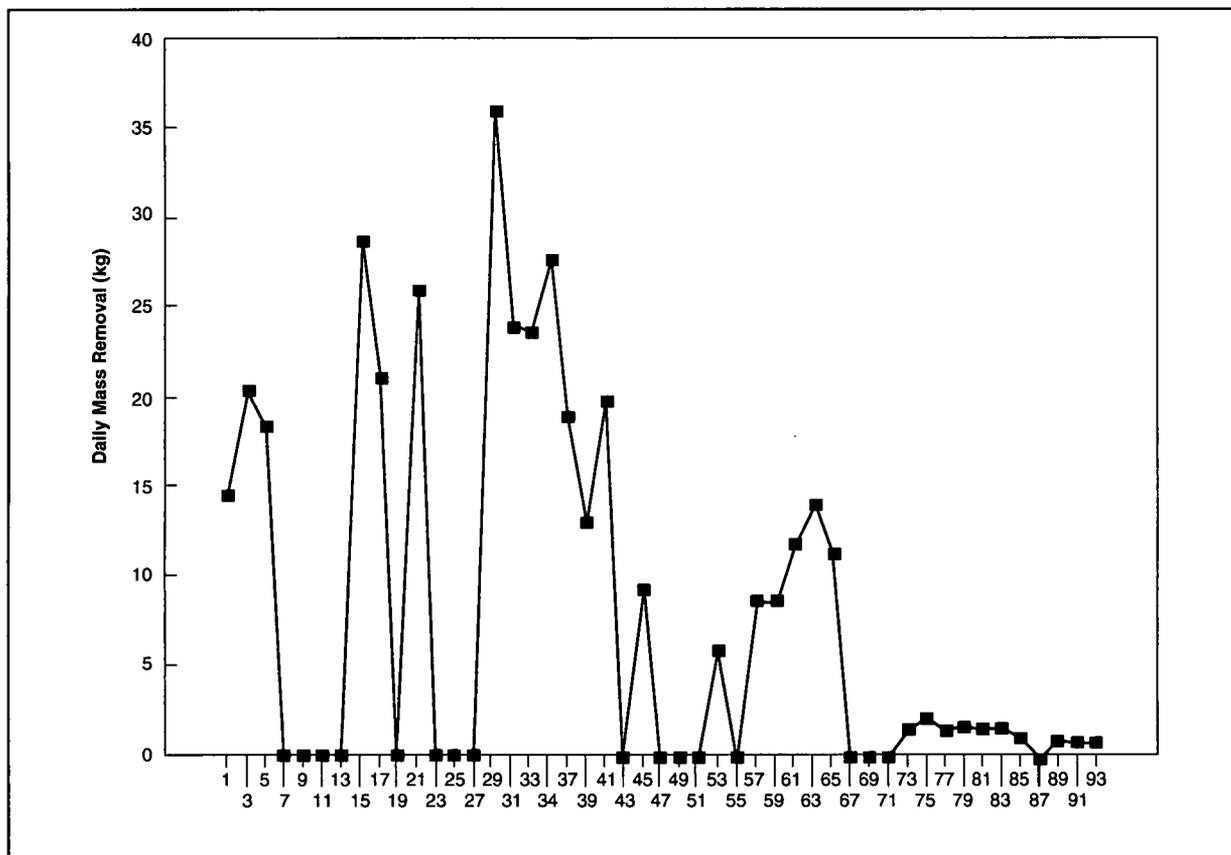


Figure 7-2 Daily contaminant removal

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**Table 7-4**  
**Total Hydrocarbon Air Emission Calculations**

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$$ER = [(Q \times C \times MW \times 2.68 \times 10^{-3}) \text{ (kg/1000g)}]$$

where

ER = emission rate (kg/hr)

Q = blower pumping rate (m<sup>3</sup>/min)

C = soil gas concentration (ppm-v)

MW = molecular weight of contaminant (g/g mole)

The constant ( $2.68 \times 10^{-3}$ ) has units of [(g-mole min)/m<sup>3</sup> ppm-v-hr] and was derived in the following manner:

$$[(1/10^6 \text{ ppm-v}) \times (60 \text{ min/1 hr}) \times (1\text{-mole}/0.0224 \text{ m}^3)] = 2.68 \times 10^{-3}$$

#### CALCULATIONS

$$Q = 7.08 \text{ m}^3/\text{min}$$

$$C = 302 \text{ ppm-v (total hydrocarbons)}$$

$$MW = 177 \text{ g/g mole (weathered gasoline, USEPA, 1991)}$$

$$ER = [(7.08 \times 302 \times (1.77 \times 10^2) \times (2.68 \times 10^{-3}) \times 1/1000)]$$

$$ER = 1.01 \text{ Kg/hr}$$

$$ER = 24.2 \text{ Kg/day}$$

Source: after USEPA 1989d

The equation above is based on the following assumptions:

- 1) Standard temperature (0°C) and pressure (one atmosphere, or 760 mmHg)
  - 2) Negligible change in air density
  - 3) Constant concentration
  - 4) Constant average molecular weight
-

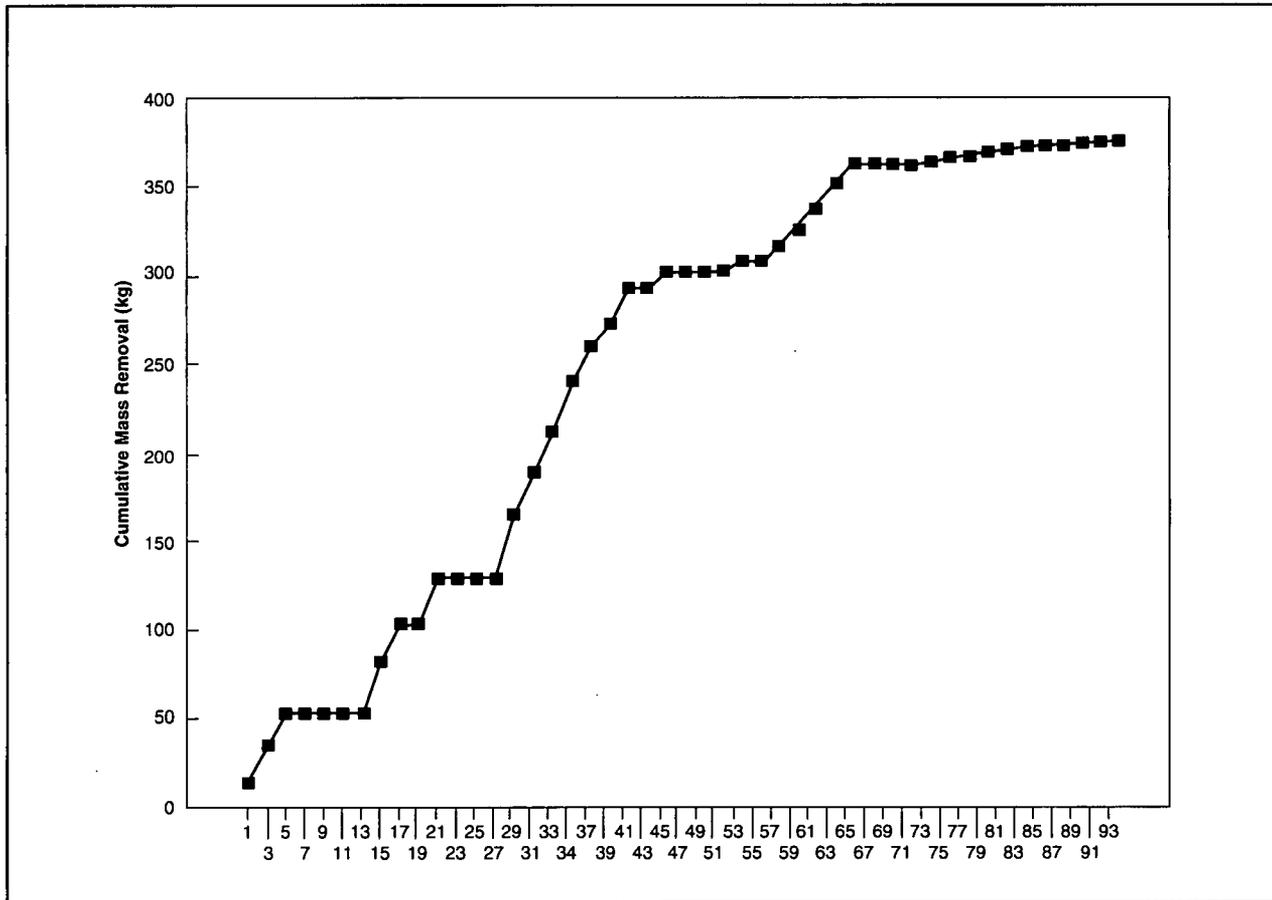


Figure 7-3 Cumulative contaminant removal

## Chapter 8 Operations and Maintenance

### 8-1. Introduction

This chapter presents guidance for performing appropriate operation, maintenance and monitoring (OM&M) for an SVE/BV system after the start-up and commissioning phases described in Chapter 7 are complete. Since initial OM&M activities are conducted during the start-up phase, Chapter 7 should also be referred to when planning this phase of remediation

### 8-2. O&M Strategy

This section presents an overview of a typical OM&M strategy, including operational guidelines, monitoring parameters, and system modification considerations. The basic monitoring protocol should have already been set when planning the start-up procedures discussed in Chapter 7. The OM&M plan may also take the form of a long term monitoring plan (LTM), and sampling and analysis plan (SAP). Table 8-1 is a troubleshooting guide for major operational problems of SVE/BV systems. The risks of encountering the operational problems listed in Table 8-1 can be reduced by proper implementation of the site characterization, bench-scale study, and pilot study phases of the project; however, the uncertainties cannot be totally eliminated due to the uncertainty inherent in employing in situ technologies. Operational problems, such as those listed in Table 8-1 may be encountered despite the best efforts to avoid them. Therefore, the design should be as flexible as possible and the OM&M plan should include contingencies for possible operational problems.

a. The system OM&M plan is typically developed based on three areas of consideration: project needs, site considerations, and system design. The plan then generally addresses the routine procedures for operation, maintenance, sampling, analysis, and system modification, as well as nonroutine activities such as troubleshooting and shutdown. It is important that the design philosophy, and especially the assumptions adopted in the design, be included in the operational requirements of the system. In order to ensure that this occurs, and to enable system modifications to be as effective as possible, the system designers should ideally remain involved during operation.

b. *System Performance Evaluation and Optimization.* One important aspect of the overall strategy is to periodically evaluate the performance of the system, both the aboveground equipment and subsurface performance. There must be some entity involved in the project that has the responsibility to see that the evaluations are periodically done. Evaluation and optimization is often best performed by an independent review team. Operational data must be available to support the evaluation. Data are collected more frequently during the early, transient stages of operation, and the sampling and monitoring frequencies are reduced as the system moves toward steady-state. Another aspect is to optimize the system to achieve maximum contaminant removal rates at minimum costs as quickly as possible. The strategy generally involves collecting data frequently enough to identify and ensure the continuity of trends. It is important that complete and thorough data sheets are maintained and reviewed in order to track these trends. To support the thorough and consistent evaluation and optimization of these systems, the USACE has prepared checklists meant to guide the users through the process. These checklists have been developed as part of the Remediation System Evaluation (RSE) process developed at the USACE HTRW CX and are available, along with an instruction guide and a sample scope of work, at

<http://www.environmental.usace.army.mil/library/guide/rsechk/rsechk.html>. Checklists are available for guiding the evaluation of subsurface performance of both soil vapor extraction and bioventing. These checklists identify the data needed to perform the evaluation, guide the analysis of the data to evaluate performance, help identify potential problems, and offer alternate technologies that may improve performance or remediation. In addition, checklists are available to guide the evaluation of the performance and maintenance of the aboveground equipment, including blowers, piping, and common offgas treatment devices such as vapor-phase carbon and thermal oxidizers.

c. The initial site model should be periodically updated to include operational data. The updated model can then be used as a basis for further system modification or optimization.

d. The operation strategy may include plans to transition from SVE to BV, or to alter/enhance SVE with ancillary technologies such as air sparging, soil heating, and pneumatic fracturing. Consequently, it will be important to monitor information that would influence the modification of the SVE, or the integration of the SVE system with another technology. For example, for a project that involves BV of fuel oil, it would be useful to track the relative volatility shift in the petroleum hydrocarbon fingerprint of the soil vapors.

e. The O&M plan should contain detailed procedures for monitoring the various physical, chemical, and biological parameters associated with the SVE/BV system. A comprehensive list of these parameters is provided in Table 8-2, although many systems will not need to monitor the entire table.

f. Pulsed venting is a mode of operation for an SVE/BV system whereby the airflow is turned off for some period of time and subsequently turned back on. Reasons for pulsed venting include the following:

(1) Cycling between wells would allow a single blower and treatment system to operate a multiwell system without dividing the total flow rate among the wells. Cycling among wells also helps to avoid the establishment of stagnation points.

(2) In diffusion-limited soils, the concentrations will tend to rebound when the system is shut off. Although the total project duration would increase, the operating time of the SVE/BV system may decrease.

(3) As the more volatile components are removed, it may be advisable to shift the system from SVE to BV. Meeting the oxygen requirements of BV may not require continuous extraction of vapors, or continuous injection of air. During BV, moving air is usually not necessary when soil gas oxygen levels are above a threshold value (refer to paragraphs 3-2*b* and 3-2*c*).

(4) Studies indicate that pulse venting may be more efficient than continuous operation in removing contaminant mass (Oster and Wenck 1988). Brailey and Rog (1989) concluded that pulsed extraction met with mixed results, although generally favorable. The concentration levels did not consistently appear to rebound upon shut off (see Figure 7-1).

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**Table 8-1. SVE/BV System Operation Strategy and Troubleshooting Guide**

| <b>Problems</b>   | <b>Considerations</b>   | <b>Potential Solutions</b>   |
|---|---|--|
| Vadose zone air flow rates in the area of concern are insufficient or not as predicted                              | The soil may be less permeable in some locations or there may be preferential flow pathways   | Further subsurface investigation<br>Readjust flows<br>Install additional wells<br>Check wells for clogging<br>Check for short-circuiting                             |
| Vacuum levels, and therefore pore gas velocities, are spatially inconsistent  | There may be preferential flow or heterogeneities   | Further subsurface investigation<br>Install additional wells<br>Seal preferential pathways   |
| The VOC concentrations have been reduced in some but not all wells  | Treatment may be completed in some areas of the site  | Reduce flow to/from wells where remediation appears complete<br>Take some wells offline<br>Check for ongoing sources of contamination                                |
| The VOC concentrations remain consistently high despite high mass removal rates                                     | Undiscovered groundwater contamination, free-phase product, or continuing source  | Further investigation (particularly for continuous source)<br>Product recovery<br>Groundwater remediation<br>Air sparging  |
| Low concentrations of VOCs are extracted during operation, but high concentrations reappear when system is shut off | Diffusion limitations, water table upwelling, seasonal water table fluctuations, flow short-circuiting due to preferential flow, soils too moist, airflow rates higher than necessary | Dual phase extraction<br>Pulse venting<br>In situ thermal treatment<br>Excavation of "hot spots" and ex-situ soil treatment  |
| Continued high levels of less volatile components   | This is likely to occur when SVE is applied to a contaminant mixture with a large range of volatility   | Concentrate on bioventing<br>Pulsed venting<br>Soil heating enhancements   |
| A decline in concentration levels has made thermal/catalytic oxidation economically infeasible                      | "Tailing" of the concentration versus time curve is a common occurrence   | Evaluate uncontrolled air emission<br>Switch to activated carbon and/or biofiltration<br>Use other technologies to speed up removal<br>Possibly reduce airflow rates |
| Poor SVE/BV performance following large rain events   | The system is sensitive to the effects of soil moisture on air permeability and aeration  | Cap site to reduce infiltration<br>Dual phase (groundwater) recovery<br>Shut off system following major rain events  |
| Unexpectedly high vapor concentrations at or near explosive levels  | Free-phase product;<br>Accumulation of methane or other VOCs  | Dilute intake air<br>Alter system to be explosion-proof<br>Check for unknown sources of contamination  |

(5) Pulsed venting also impacts the efficiency of the offgas treatment system. Activated carbon will adsorb organic compounds more efficiently at higher concentrations; therefore, pulsing would tend to reduce carbon usage. Thermal treatment also benefits from higher concentration levels, in that supplemental fuel requirements are reduced. However, a start-up period is necessary to allow these units to reach the proper operating temperature. Thus, fuel consumption could increase if the system is frequently started up and shut down. The amount of operator attention required could also increase.

(6) For BV systems, the airflow rate requirements decrease as the concentrations in the soil and thus the oxygen uptake rate diminish. These systems are typically controlled by monitoring the concentrations of oxygen in the vadose zone and maintaining the concentration above a predetermined level capable of supporting aerobic biological activity (e.g., 5 percent O<sub>2</sub>). A sufficient number of monitoring points must be properly placed to determine if vadose zone oxygen levels are being maintained. Sorensen and Sims (1992) suggest that there are advantages to alternating between anaerobic and aerobic conditions during pulsed venting. Anaerobic conditions may allow for beneficial reaction pathways to develop, such as nitrogen fixation. Injection of air and an organic substrate (e.g., methane, propane, etc.) has been demonstrated for in-situ bioremediation of some chlorinated solvents (e.g., TCE), and has been termed cometabolic bioventing. This type of cometabolic process occurs under aerobic conditions; oxygen is the electron acceptor, and the organic substrate is the electron donor. It just so happens that the enzyme used by the bacteria to metabolize the organic substrate also catalyzes breakdown of TCE. The bacteria are not believed to derive energy from TCE degradation.

*g. Aboveground soil pile treatment system operation.*

(1) OM&M of aboveground soil piles is generally the same as SVE/BV systems.

(2) If bioremediation is to be optimized in the aboveground soil treatment system, maintenance of moisture levels within a predetermined range is important to optimize system performance. If an irrigation system is incorporated into the soil pile treatment system, careful control must be exercised over the frequency and volume of irrigation water applied to the soil pile. In addition, because the movement of air through the soil pile will have a tendency to remove moisture from the pile, some consideration must be given to providing a water-knockout tank of appropriate size, or installation of an automated knockout drainage system.

### **8-3. Monitoring**

Monitoring is performed during the operational phase to evaluate whether the remediation equipment is functioning as designed and whether the remediation is progressing as predicted. The OM&M plan should list the parameters to be monitored and analyzed (see Table 8-2 for guidance), the accuracy and precision required and a schedule for collecting the information. Additional discussions of monitoring methods are described in Chapters 3, 4 and 7.

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**Table 8-2. Suggested SVE/BV System Monitoring Checklist**

---

**Meteorological**

Precipitation  
Barometric pressure  
Ambient Temperature

---

**Physical Characteristics**

Pressure at SVE well(s)  
Pressure at vadose zone monitoring wells/points  
Contaminant concentration at vadose zone monitoring points  
Pneumatic logging (to determine differences in permeability, and contaminant levels, as a function of depth along the well screen)  
Blower inlet vacuum  
Blower outlet pressure  
Vapor temperature at wellhead  
Temperature at blower discharge  
Temperature at treatment effluent  
Wellhead volumetric airflow rate (acmm)  
Blower inlet flow rate (acmm) (upstream from the inlet bleed valve)  
Treatment effluent flow rate (acmm)  
Bleed rate (acmm) (possible to estimate as the difference between airflow rates upstream and downstream from the inlet bleed valve)  
Blower amperage  
Volume of condensate  
Soil moisture content  
Relative humidity in extracted soil vapor  
Groundwater elevation(s) near extraction well(s)  
Degree of upwelling  
Volume of groundwater removed (if any)  
Volume of free product removed (if any)

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**Chemical Characteristics**

Contaminant concentrations at extraction well(s)  
Contaminant concentrations at blower inlet (upstream from the inlet bleed valve)  
Contaminant concentrations at treatment influent  
Contaminant concentrations at treatment midpoint (e.g., between activate carbon vessels)  
Contaminant concentrations in treatment effluent  
Contaminant concentrations in soil gas at monitoring points  
Contaminant concentrations in extracted groundwater  
Contaminant concentrations in condensate  
Contaminant concentrations and oxygen levels in work area (per Site-specific Safety and Health Plan)  
Contaminant concentrations at site perimeter (per regulatory requirements)

---

**Biological Characteristics (see Table 3-1 for analytical methods)**

Bacterial enumeration (optional)  
Oxygen concentrations (may be applicable to both bioventing and SVE)  
Carbon dioxide concentrations (may be applicable to both bioventing and SVE)  
Microbial respiration rate (shutdown tests)  
Nutrient concentrations (e.g. nitrogen and phosphorus)  
pH

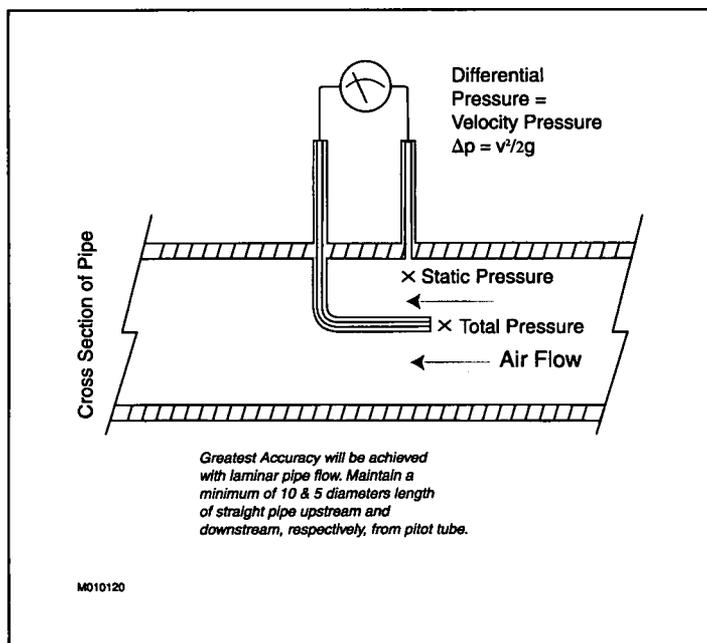
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a. *Physical parameters.*

(1) Vacuum / pressure measurement. Vacuum / pressure readings must be collected and can be measured with manometers, Magnehelic® gauges, or pressure transducers. For critical data collection points like the extraction well(s) and certain monitoring wells, it is suggested that electronic pressure transducers, in conjunction with an automatic data logger, be used to record the data at regular frequent intervals. Over time, the data logger provides a cost-effective alternative to taking manual readings, especially at remote sites. The data can be downloaded via computer modem. However, the data should be verified periodically with manual readings.

(2) Vapor velocity measurement and flow rate calculation. Vapor flow rates must be measured at each extraction and injection well. Flow rates should also be measured at the ambient air inlet and downstream of the ambient air inlet, prior to the blower. The ambient air bleed rate can be double-checked by subtracting the individual extraction well flow rate(s) from the total flow at the blower inlet.

(a) Measurements can be made using a variety of flow meters, including rotameters, hot-wire anemometers, and flowmeters based on a differential pressure reading inside the pipe. Such pressure related flowmeters include venturi meters, orifice plates, averaging pitot and pitot tubes. For most SVE applications, the amount of pressure drop caused by rotameters is not acceptable. Pitot tubes and hot-wire anemometers are typically the most appropriate measuring devices. However, the presence of water in an airstream reduces the accuracy of all flowmeters, and can damage hot-wire anemometers.



(b) Pitot tubes are the most commonly utilized flow measurement in SVE/BV systems. The pitot tube consist of two pressure ports, one perpendicular to flow (static pressure port) and one pointed directly into the flow (stagnation or total pressure port). The differential pressure between these two ports is referred to as the velocity pressure and is a function of velocity. A typical installation of a pitot tube in a small diameter pipe is shown in Figure 8-1.

Figure 8-1 Pitot tube flow measurement schematic

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Bernoulli's equation can be used to derive the relationship between velocity and velocity pressure:

$$p_t + h_t + v_t^2 / (2g) = p_s + h_s + v_s^2 / (2g) \quad [\text{Bernoulli's equation.}] \quad (8-1)$$

where the subscript *t* represents the property at the total pressure port and the subscript *s* represents the static pressure port.

For SVE/BV systems,  $h_t = h_s$  and  $v_s = 0$ . Therefore:

$$\Delta p = p_s - p_t = v_t^2 / (2g) \quad (8-2)$$

and

$$v = v_t = \sqrt{2g\Delta p} \quad (8-3)$$

In equation 8-3, the differential pressure (or velocity pressure) is the height of fluid (air) and velocity is in length per unit time. However, differential pressure gauges do not have "height of air" scales, but usually have scales in units of mm water, cm water, or mm mercury (Hg). Differential pressure may also be reported as Pascals ( $\Delta P$ ; force per unit area), which can be related to height of fluid:  $\Delta P = \rho_{\text{air}} \times g \times \Delta p$ . Rearranging and substituting into equation 8-3:

$$v_t = \sqrt{2\Delta P / \rho_{\text{air}}} \quad (8-4)$$

Height of fluid is related to units for the measuring device (i.e., height of water or height of mercury) by:  $\Delta p_{\text{air}} = \Delta p_{\text{md}} \times \rho_{\text{md}} / \rho_{\text{air}}$ , where *md* refers to the units for the measuring device (e.g., mm of water). Therefore:

$$v_t = \sqrt{2g\Delta p_{\text{md}} \frac{\rho_{\text{md}}}{\rho_{\text{air}}}} \quad (8-5)$$

Note again that velocity for the pitot tube is a function of the density of air. Only when  $\rho_{\text{air}} = \rho_s = \rho_{\text{standard}}$ , where the pressure and temperature at the static pressure port is at standard conditions (i.e., 20°C and 1 atm), can standardized charts be used without a correction for temperature and pressure.

(c) Pitot tubes relate velocity to pressure at the point of the stagnation port, generally placed in the center of the pipe. SVE/BV systems typically use pipe smaller than 150 mm, and measuring the velocity in the pipe at any point other than the center of the pipe is not practical. The velocity at the center of the pipe is the maximum velocity within the pipe and the velocity near the wall of the pipe approaches zero. Best engineering practice for compensating for the non-uniform velocity profile across the cross-section of the pipe is to use an integrated average velocity, often assumed to be 0.9 times the velocity in the center of the pipe. The velocity is used to calculate the volumetric flowrate, *Q*. Typically the measured flowrate,  $Q_{\text{measured}}$ , is obtained by assuming that the measurement point is at standard temperature and pressure

conditions, i.e.,  $\rho_{\text{air}} = \rho_{\text{standard}} = 1.2 \text{ kg/m}^3$ . For differential pressure expressed as force per area (e.g., pressure in Pascals or psi):

$$Q_{\text{measured}} = 0.9 \frac{\pi d^2}{4} \sqrt{2\Delta P / \rho_{\text{standard}}} \quad \text{or} \quad (8-6)$$

$$Q_{\text{measured}} = 1.0 d^2 \sqrt{\Delta P / \rho_{\text{standard}}} \quad (8-7)$$

For differential pressure expressed as height of water or height of mercury:

$$Q_{\text{measured}} = 0.9 \frac{\pi d^2}{4} \sqrt{2g\Delta p_{\text{md}} \frac{\rho_{\text{md}}}{\rho_{\text{standard}}}} \quad \text{or} \quad (8-8)$$

$$Q_{\text{measured}} = 1.0 d^2 \sqrt{g\Delta p_{\text{md}} \frac{\rho_{\text{md}}}{\rho_{\text{standard}}}} \quad (8-9)$$

(d) Larger pipe can be fitted with a pitot tube which is constructed of concentric tubes that has the static pressure port located in the outer tube, while the stagnation pressure port is the tip of the inner tube.

(e) Averaging pitot tubes work on the same principle of relating differential pressure within the pipe to air flowrate. Differential pressure is obtained with an averaging pitot tube by measuring pressure at ports in the upstream and downstream sides of a tube (typically 8 to 16 mm diameter) inserted into the pipe perpendicular to flow. There are a series of pressure ports along the tube which pneumatically "average" the differential pressure profile of the cross-section of the pipe. The equations relating this average differential pressure to flowrate are specific to each averaging pitot tube manufacturer. Averaging pitot tubes are more accurate than conventional pitot tubes and can easily be moved from one measurement location to another. Thus, by simply installing measurement ports with compression seals at various locations in an SVE/BV system, flow measurements can be made for the system using a single averaging pitot tube and differential pressure gauge.

(f) It is desirable to report flow rates normalized to a standard temperature and pressure so that flows can be readily compared. Airflow measuring equipment may be calibrated to air at different temperature and pressure than the air flowing through the SVE/BV system. (If airflow measuring equipment is calibrated, it is typically calibrated at standard conditions.) Calibrated gauges must be matched to the correct measuring devices and inside pipe diameter. In some instances, the gauges will have dual scales, with one scale indicating the velocity pressure, and the other indicating the air velocity or flowrate. Direct velocity or flow readings must be corrected to account for the differences between the temperature and pressure of the air being measured, and the temperature and air when the instrument was calibrated. The temperature and pressure (and therefore density) of air in a pipe between an SVE well and blower will be significantly different than the conditions of the air exiting the SVE blower. Therefore, volumetric airflow rate measurements at these two locations are not directly comparable and the measured airflow rates must be corrected for the density difference between the measured conditions and the conditions under which the device was calibrated. Only at the calibrated density, would a flow meter not require correction to obtain a

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standardized flow rate or velocity. With the exception of high-end electronic flow meters that can compute an internal correction for air at the measured temperature and pressure (i.e., density), airflow meters do not provide a direct reading (i.e. without needing correction for air density) of standard flow or actual flow. (Standard flow refers to the equivalent flowrate if the air was flowing at standard conditions. Actual flow refers to the flowrate at the temperature and pressure that exists at the point of measurement.)

(g) "Measured" flowrate may be directly read from a gauge that has a scale for direct reading of airflow rates, or may be stored electronically by a data logger in a system with automated data acquisition. The corrected standardized flowrate ( $Q_{\text{standard}}$ ) is equal to the product of the measured flowrate ( $Q_{\text{measured}}$ ) and the square root of the ratio of the density at the calibrated (standard) conditions and the density of the air being measured.

$$Q_{\text{standard}} = Q_{\text{measured}} \sqrt{\frac{\rho_{\text{actual}}}{\rho_{\text{calibrated}}}} \quad (8-10)$$

Applying the ideal gas law to the density ratio provides a more practical correction equation:

$$Q_{\text{standard}} = Q_{\text{measured}} \sqrt{\frac{273 + T_{\text{calibrated}}}{273 + T_{\text{actual}}} \cdot \frac{760 + P_g}{P_{\text{calibrated}}}} \quad (8-11)$$

where  $P_g$  is gauge pressure in mm Hg;

$T$  is temperature in °C; and

$P_{\text{calibrated}}$  is the absolute pressure in mm Hg at the calibrated conditions.

Applying the assumption of calibration at standard conditions:

$$Q_{\text{standard}} = Q_{\text{measured}} \sqrt{\frac{293}{273 + T_{\text{actual}}} \cdot \frac{760 + P_g}{760}} \quad (8-12)$$

OR

$$Q_{\text{standard}} = K_{pt} Q_{\text{measured}} \quad (8-13)$$

where  $K_{pt}$  is the Correction Factor found in Figure 8-2



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(h) Equation 8-12 and 8-13 should be used to calculate air emission rates (see Table 7-4), which are based on the extracted flowrate and vapor concentration (which need to be measured at the same time for accuracy). This correction is necessary for such measurements made using rotameters and for volumetric airflow measurements based on a differential pressure measurement, such as pitot tubes, venturi meters and orifice plates. In contrast, hot-wire anemometers measure the mass flux of air flowing past a hot wire and the anemometers' read-outs typically yield velocities as if the flow was under standard temperature and pressure. (Note that if the actual temperature of the air being measured is close to the temperature of the hot wire, e.g. at the outlet of a thermal oxidizer, then this device may not provide an accurate flow measurement.)

(i) An alternate method for calculating  $Q_{\text{standard}}$  is to calculate  $Q_{\text{actual}}$  (the actual air flowrate) using the actual temperature and pressure values at the measurement point, and then converting to a standard flow rate as shown below.

$$\rho_{\text{actual}} = \frac{(0.463 P_a)}{(273 + T_{\text{actual}})} \quad (8-14)$$

In the above equation, density units are  $\text{kg}/\text{m}^3$ , using units of degrees Celsius and mm Hg for temperature and absolute pressure ( $P_a$ ), respectively. In the following equation, airflow rate is obtained in  $\text{m}^3/\text{min}$ , using units of meters for inside diameter ( $d$ ), mm Hg for velocity pressure ( $\Delta p_{\text{md}}$ ), and  $\text{kg}/\text{m}^3$  for air density ( $\rho_{\text{actual}}$ ).

$$Q_{\text{actual}} = 0.9 \frac{\pi d^2}{4} 978.1 \sqrt{\Delta p_{\text{md}} / \rho_{\text{actual}}} \quad (8-15)$$

$Q_{\text{actual}}$  is then converted into a standard flow rate using the following equation. In the following equation, mm Hg and degrees C are used as units for gauge pressure ( $P_g$ ) and temperature, respectively.

$$Q_{\text{standard}} = Q_{\text{actual}} \frac{293}{273 + T_{\text{actual}}} \cdot \frac{760 + P_g}{760} \quad (8-16)$$

(3) Soil and vapor temperature measurement. Vapor temperatures should be monitored to enable the conversion of flow rates from acmm to scmm, as discussed above, and to ensure accurate determination of the efficiency of the vapor control system. The removal efficiency of activated carbon is affected by temperature. The efficiency may increase or decrease depending on the relative humidity. In addition, piping typically used for SVE/BV applications normally has a temperature limit above which the piping may fail. Soil and soil vapor temperatures would be monitored for a thermally enhanced SVE/BV system. Finally, Connor (1988) predicted that soil temperatures could indicate the level of biodegradation taking place in the contaminated zone(s). Temperatures can be measured with ordinary thermometer probes, temperature gauges, or with electronic thermocouples that provide output to data loggers.

(4) Relative humidity. The relative humidity of the extracted gas should be reduced to protect the blower and to promote the efficiency of the vapor emissions control system (i.e., the adsorptive capacity of

activated carbon is reduced significantly when the relative humidity is greater than 50%). The relative humidity can be monitored to determine the effectiveness of the condensate control system described in paragraph 5-7. Humidity or temperature monitoring can be performed and used to control a humidity reduction / air heating system. The relative humidity of the vapor stream can usually be decreased to about 50% by increasing the temperature by about 20 degrees F.

(5) Water levels. Water levels should be monitored in the area of the extraction well(s) to determine the amount of upwelling that occurs as a result of the applied vacuum. Methods of monitoring groundwater elevations are described in Chapters 4 and 7. Rainfall events can have a significant effect on SVE/BV performance, and should be noted. Local weather stations can often provide compilations of meteorological data.

(6) Air-water separator collection tank (or "moisture separator" or "demister"). The volume of water removed from the vapor stream should be monitored and recorded. The amount of water in the tank can be determined by placing a sight glass on the tank and computing the volume contained. If large volumes are produced and manually or automatically removed and discharged, these volumes should also be recorded.

(7) Blower amperage. Blower amperage should be monitored as a means of determining the load placed on the blower. Excessive amperage may indicate low flow and/or high vacuums across the blower, which could lead to overheating. The amperage can usually be measured at the blower control box using a basic ammeter. The data should be compared with the suggested operating range supplied by the blower manufacturer. Excessive amperage can be resolved by opening the ambient air inlet valve slightly to allow more flow through the blower. This will, however, reduce the vacuum throughout the soil matrix, so the minimum bleed rate should be used to minimize the reduction in the zone of influence. It is important to note that excessive amperage (and thus, excessive strain on the blower) may indicate that the blower is undersized, or that excessive upwelling has occurred in the extraction well(s), or that the well screen(s) have become clogged. These scenarios should be considered and investigated should excessive amperage be found consistently.

(8) Blower and pump run-time and on/off cycles. For blowers designed to operate intermittently, control panels typically include a clock that records cumulative hours of run-time and an odometer-type device that records the number of on/off cycles. This information can prove invaluable should a power outage occur while the unit is unattended, as it enables the operator to determine the time and sometimes the cause of the outage. Similarly, if groundwater and/or NAPL is being pumped to the surface as part of dual recovery system (see paragraph 3-2e), measurement of gallons pumped using a flowmeter can be augmented with pump run-time and on/off cycle data.

*b. Chemical.* The goals of chemical monitoring are to monitor the effectiveness of the air emission control system and assure that the offgas is within limits; track contaminant mass removal rates; and monitor subsurface chemical conditions.

(1) Prior to start-up of the SVE/BV system, a long-term monitoring plan will have been established and included within the SAP or the O&M manual. The monitoring plan should specify the location of sampling points, frequency of sampling, methods for sampling and analysis, and quality assurance / control requirements (see Chapter 3).

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(2) The plan should include more frequent monitoring during system start-up and initial operation. Once the system is optimized, the monitoring frequency and intensity can often be reduced. It may be possible to employ screening methods or analyze for only indicator compounds. Often the chemical constituents do not change over the life of a project; therefore, simpler, less expensive analyses may be sufficient. However, where a mixture of contaminants is present, as in the case of fuel hydrocarbons, more volatile constituents will be depleted first, after which analytical attention may be shifted toward less volatile constituents. See paragraphs 7-4c, and 3-3d for more detail regarding field and laboratory analyses.

(3) System shutdown criteria, which will be discussed in the next chapter, play a strong role in determining the monitoring strategy. Monitoring must primarily demonstrate that the treatment goals are being achieved. For example, if the shutdown criteria require that soil vapor concentrations be reduced to a certain level, the monitoring plan could include provisions for temporarily shutting down the SVE/BV system to allow concentration levels to recover and then measuring VOC concentrations in the soil vapor.

(4) VOCs are monitored to determine the effectiveness of the air emission control system. For activated carbon, VOCs are typically measured before, after, and between carbon canisters. The required frequency of monitoring is determined by conservative carbon usage calculations. Since carbon usage typically decreases during the life of the project, provisions should be made to decrease monitoring frequency. Monitoring is typically performed using a field instrument with less frequent laboratory analysis.

(5) It may be necessary to monitor for compounds other than VOCs. For thermal and catalytic oxidation systems, combustion of halogenated VOCs could create acid fumes; therefore, acid monitors should be employed if halogenated VOCs are suspected.

(6) Chemical and flow rate monitoring of the SVE system influent (or BV system influent, if applicable) should be used to calculate the contaminant mass removal rates from the subsurface. The flowrate and contaminant concentration must be measured at the same time to obtain accurate mass removal rate data. The method for calculating this was presented in Table 7-4 of the previous chapter. This mass removal rate can be compared with an estimate of the initial mass of contaminants in the subsurface. A complete mass balance would also require inclusion of the mass of contaminants that are biodegraded. This latter value may be difficult to assess however. Refer to the discussion in Chapter 4 on in situ respirometry.

(7) Chemical monitoring (i.e., periodically performing soil gas surveys) of the subsurface soil gas will also help gauge the progress of the remediation. Soil gas samples for VOC analysis should be obtained from the effluent of the vacuum blower, from individual extraction wells, and from soil gas probes, air piezometers, or water table monitoring wells. As described in paragraph 7-4c(4), the specific components of the soil gas can be analyzed by gas chromatography or the total amount of VOCs present can be measured with explosivity meters and flame- or photo-ionization detectors. For more frequent (even continuous, if desired) or automated vapor phase chemical monitoring, such instruments can be set up to sample with an air pump and analyze soil gas on a fixed schedule and then transmit the data over a telemonitoring system or store the results using a datalogger. Monitoring the concentrations of oxygen, carbon dioxide, and sometimes methane helps establish the level of biological activity in the subsurface (see paragraph 8-3c).

(8) Chemical analysis of accumulated condensate from the moisture separator is usually required for discharge or disposal purposes. If the volume of condensate is significant, the concentrations can be used to calculate the amount of contaminant mass being removed via the dissolved phase.

*c. Biological.* Biological degradation (biodegradation) of both volatile and non-volatile contamination is an important process in soil vapor extraction and is a critical process for bioventing. Monitoring of biological activity before and during bioventing can be accomplished by several means in addition to observing changes in the contaminant concentrations themselves (see Chapter 3 for information on microbial activity assays).

(1) Microbiological tests can be used to screen for conditions which may be toxic to microorganisms. Toxic conditions could, for example, be caused by excessive contaminant concentrations, heavy metals, or other environmental factors. Changes in the toxicity of soil water extracts can signal when toxic conditions are alleviated, such as through pretreatment of soil prior to construction of an aboveground pile. The Microtox™ test is one commonly used and is a relatively inexpensive assay which involves exposing a specific strain of luminescent bacteria to a sample and then measuring the light output of the bacteria after exposure under standard, reproducible conditions. The light output is compared with that of a control, and a difference in light output is attributed to the degree of toxicity of the sample. The more the luminescent bacteria are challenged by the presence of toxins, the lower is their light output.

(2) Soil Gas Composition. Concentrations of oxygen and carbon dioxide in the soil gas are routinely monitored during BV operations using portable gas meters; and should be monitored at SVE sites when the contaminants are amenable to biodegradation. It is important that portable meters have the capability to measure wide ranges of concentrations with adequate sensitivity. If carbon dioxide concentrations exceed the range of the meter, the sample can be diluted with ambient air. Significant deviations from ambient conditions (dry atmospheric air contains approximately 20.9 percent oxygen and 0.03 percent carbon dioxide) in soil gas are possible in soil undergoing "natural" biodegradation. Prior to BV at one site, 0 percent oxygen and 26.4 percent carbon dioxide were measured in soil gas (Hinchee, Ong, and Hoeppe 1991). Such low oxygen and high carbon dioxide concentrations provide an indication of aerobic biological activity. High concentrations of methane, which can also be measured with portable gas meters, have been observed and can be attributed to anaerobic biodegradation. If bioventing is delivering sufficient air to the subsurface, the soil gas composition should be closer to atmospheric conditions. Aerobic activity should also be stimulated and anaerobic reaction should cease producing methane, although in low permeability strata, methane may continue to be produced.

(3) Respiration rate determinations. One way to evaluate in-situ biodegradation and bioventing in the vadose zone is to periodically perform an in-situ respiration test. This is done by first measuring oxygen and carbon dioxide concentrations in soil gas extracted from extraction and monitoring wells in the remediation zone during or immediately after many weeks of bioventing. The bioventing is then stopped and these gas concentrations are measured over time. Typically, if contamination or other organic matter still exists, oxygen is consumed and carbon dioxide is produced. If one assumes a stoichiometric relationship between oxygen consumption or carbon dioxide generation and contaminant biodegradation, contaminant biodegradation and removal rates can be estimated. Care should be taken, however, to account for other abiotic sources and sinks such as oxygen consumption (e.g., in oxidizing native organic matter or ferrous iron) or diffusion and carbonate cycling since the subsurface is not a closed system. Having fewer abiotic sources and sinks, oxygen is generally recommended over carbon dioxide for determining biodegradation rates (Ong et al. 1991). By performing these respiration rate determinations periodically (quarterly to annually depending on the expected rate of change) and observing changing rates,

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the progress of the bioventing and contamination reduction can be evaluated. The observed rates could be compared to rates that may have been measured in laboratory respiration tests. This information can also be used to optimize BV flow rates which deliver oxygen to the soil. Sayles et al. (1992) suggest maintaining oxygen concentrations above 5 percent to avoid oxygen limitation of microbial activity.

*d. Aboveground soil pile treatment system monitoring.*

The aboveground soil pile treatment system should require a minimal level of system monitoring. Methods of system monitoring are typically consistent with measures implemented for SVE/BV treatment systems.

(1) Soil gas monitoring. Permanent soil gas probes used in SVE/BV can be used in soil piles. However, they are usually hand-installed during or after soil pile construction. Care must be taken to assure that tubing/piping to soil gas probes do not serve as pathways of preferential airflow. Levels of oxygen, carbon dioxide, and total petroleum hydrocarbons are typically monitored under two regimes:

Concentrations as a function of time after blower shutdown.

Concentrations as a function of time after blower start-up.

The measurement regimes will allow assessment of biological activity, airflow efficiencies, advection/diffusion limits, etc. Respirometry data reduction is performed in a manner identical to BV data reduction.

(2) Soil sample collection and analyses. Soil samples may be taken periodically to assess progress toward a soil-concentration based cleanup goal. Soil sample collection is typically conducted using hand-augering tools and hand-driven sampling devices. Once samples are retrieved, some effort should be made to backfill hand-borings in such a manner that preferential airflow pathways are not created. Chemical analyses are performed in the same manner as for in situ SVE/BV. Note that heterogeneous distribution of contaminants in soil may obfuscate expected trends in the data. Statistical analyses of sets of samples may be necessary to identify trends in soil concentration data (see Chapter 9).

#### **8-4. Venting Well Maintenance**

*a.* The maintenance of a venting well includes measures to ensure that the vapor being drawn through the wells is unimpeded and contributed from the entire zone of influence for which the well was designed. This implies that the venting well must be kept airtight and free of debris or biological or chemical buildup which could clog the well screen.

*b.* One of the leading causes of vapor short-circuiting is a dried-out, cracked casing seal, which is fairly common in certain types of grout when subjected to a vacuum. After a period of time, all the moisture is evacuated from the grout, forming cracks which allow preferential vapor flow down the sides of the casing. As the cracks progress and the grout shrinks, vibrations of the well casing tend to intensify the damage. This situation can be detected, however, by carefully pressurizing the well (avoid over-pressurization) and checking for leaks using soap solution. An alternative method is to simply pour 3 to 4 liters of water onto the grout around the well casing and observe the time it takes for the water to permeate the grout. A severely damaged seal will absorb the water in a matter of minutes, while a good seal should be capable of holding the water for upwards of an hour. If the seal is slightly damaged, an

additional layer of grout could be placed over the existing layer (with the extraction system shut off) in order to seal the cracks. However, if the damage is significant, the well must be replaced.

### 8-5. Vapor Collection System OM&M Considerations

*a. OM&M design considerations.* Operations and maintenance requirements should be taken into account early in the design of the SVE/BV system. There are, however, requirements for maintaining equipment that cannot be designed away. Operating a unit can be completely automatic (more expensive), semi-automatic with operator interface, or manual. The system design will include trade-offs between capital costs and OM&M costs. Needs for operator involvement depend on the size of the unit, the importance of keeping the unit running full time, the phase of cleanup (i.e. start-up operations or the final stages of cleanup), and other factors.

*b. Unit size.* The size of a unit may influence the amount of OM&M effort required. For example, one large carbon bed may not require changing for months but may be less efficient than smaller units requiring changing more often.

*c. Explosive and nonexplosive vapors.* A properly designed system will minimize fugitive vapor emissions. In the case of approved releases of VOCs directly to the atmosphere, release points should be located away from sensitive receptors and potential sources of ignition. Explosion hazards should be considered relative to other aspects of the SVE/BV systems as well.

(1) Some vacuum pumps generate high discharge temperatures. If these units push high-temperature gases into carbon beds, there is the possibility of spontaneous combustion that can produce even higher temperatures, thereby propagating the combustion. Starting an internal fire fanned by a vacuum pump or blower is possible. If the concentration of organic vapors falls between the upper and lower explosive limits, the possibility of explosion exists.

(2) Vacuum pumps have internal clearances that affect efficiency. If a rotary lobe vacuum pump is poorly maintained and has a bearing or lobe failure, the unit may be damaged beyond repair. Also there is greater potential for a poorly maintained unit to create a fire hazard, especially if high concentrations of organics are being extracted.

(3) Thermal oxidizers by nature operate at high temperatures. Again, a flame arrestor should be included to preclude the possibility of fires.

(4) Carbon canisters can sometimes contain high concentrations of VOCs that can leak into the surrounding atmosphere during the changing of these units. The equipment should include valves to isolate the liquids and fumes before piping, hoses, or ducts are disconnected, as well as provision for fire protection/suppression (see paragraph 5-12*b*).

(5) To avoid static electricity buildup, all equipment should be grounded as should the building and other items inside the building where the process equipment is installed.

(6) The National Fire Protection Association (NFPA) prepared a guide on hazardous materials (1994) which includes data on flashpoint, specific gravity, water solubility, hazard identification, and boiling point

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for flammable liquids, gases, and solids. Material safety data sheets assembled for a site will contain information on the physical and chemical properties for contaminants of concern. Fire hazard data are also included that identify combustibility, flammability, and explosivity of the compounds.

(7) Automatic shutdown systems should be included in any system that handles flammable/explosive fluids. If temperatures approach hazardous levels, warnings should be initiated and systems shut down if dangerous conditions are reached. Fire protection systems, such as sprinklers and blast doors should back up these shutoff systems.

*d. Operator training.* Formal operator training is needed to adequately prepare site operators to safely and effectively operate and maintain the SVE/BV equipment. Training should include classroom and hands-on training.

### 8-6. System Operation Schedule

The operation time of an SVE/BV system may be partly based on offgas VOC concentrations. When VOC concentrations in the offgas fall to inefficiently low levels, the system may be turned off for a period of time so that the VOCs can diffuse into soil pores participating in advective transport. The diffusion rate is dependent upon the diffusivity of the VOC constituents, moisture content, and a variety of other subsurface conditions (refer to paragraph 8-2). Table 8-3 is a generic checklist that should be kept at the site for routine O&M checks.

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**Table 8-3. Routine Maintenance Items**

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|---|
| Periodically drain the water that has accumulated within the PVC pipe header lines.   |
| Monitor the inlet and outlet vacuum. Adjust ambient air intake and manifold valves as needed.   |
| Monitor the outlet temperature of the blower. If the blower temperature approaches the upper limit (as indicated in manufacturer's literature), decrease the vacuum or troubleshoot the unit. |
| Verify that the air water separator and transfer pump are working properly.   |
| Check daily calibrations of the VOC analyzer. Make any corrections to the analyzer response.  |
| Monitor gas cylinders for proper operating pressures and levels.  |
| Approximately every 500 hours (or per manufacturer's recommendations), re-grease blower assembly per manual.  |
| Approximately every 1500 hours, change oil in blower assembly, adding oil suitable to ambient conditions for the next quarter.  |
| Monitor pressure drop across filters, and periodically clean or replace particulate filters.  |

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### 8-7. Recordkeeping

A formal data management system is vital to efficient operation of the SVE/BV system. Vacuums/pressures, flow rates, temperatures, and other operating parameters need to be monitored and recorded. Information regarding sample location, date and time of collection, laboratory, test method, analytical results, detection limits, and associated quality control samples must be tracked. For large SVE/BV systems, a computerized data management system is suggested. Recently, all member agencies of the Federal Remediation Technologies Roundtable (including all branches of the DOD) have endorsed standardized collection and reporting of remediation performance and cost (USEPA 1995).

## 8-8. System Evaluation/Modifications/Optimization

To cost-effectively remediate sites, an increasingly important aspect of operating a SVE or bioventing system is optimization of the remedial processes. In their guide to system optimization "Draft Final Remedial Process Optimization Handbook", AFCEE, Brooks AFB, TX, (AFCEE, 1999), AFCEE reports that the DOD alone will spend over \$1 billion per year on OM&M. AFCEE recommends performing Remedial Process Optimization (RPO) evaluations at least once per year at some degree of detail. Depending on the complexity of the remediation system, the evaluation/optimization team should involve hydrogeologists, engineers, chemists, risk assessors and regulatory specialists to complete this evaluation. In addition to increasing the speed of remediation, optimization can also lead to cost savings (for example, by changing from expensive catalytic oxidation to activated carbon adsorption or biofiltration for vapor treatment).

AFCEE recommends review of the SVE from three perspectives:

1. Evaluation and optimization of the operation of the existing system with the goal of maximizing the rate of contaminant mass removal to achieve the greatest reductions in contaminant concentrations and minimize operating costs.
2. Re-evaluation of the system components (e.g., wells, blowers, offgas treatment system) to determine if changing or adding to the system will increase performance or to determine whether a wholly new technology is necessary.
3. Re-examination of the remedial goals in light of new regulations or risk evaluations are applicable.

*a. Evaluation and optimization of the existing remediation system* should be performed to accomplish the following goals: to maximize the removal rate of contaminant mass, to reduce the costs of system operation, and to reduce the amount of time it will take for the system to achieve cleanup criteria (for more information, see the Remediation System Evaluation checklists, at <http://www.environmental.usace.army.mil/library/guide/rsechk/rsechk.html>.) This evaluation should include confirming that any discharge concentration requirements are being met. The OM&M costs for achieving this degree of remedial progress should be compiled and reviewed. Often, one of the largest costs of an existing remediation system is the monitoring program. The monitoring plan should be evaluated for the potential of reducing monitoring costs or getting better data for the same costs. (However, it is important to emphasize that acquiring system performance data, such as flow rates and concentrations from individual wells is relatively inexpensive and very helpful for continuing system optimization. Most cost savings occur in reducing compliance monitoring, such as groundwater sampling by USEPA SW-846 methods.) Most system modifications are made because the soil vapor flow is not occurring where it is needed or the equipment is not functioning as designed (equipment problems will be discussed in the next section on troubleshooting). Some examples of common operational modifications that can be made to an existing system are described below.

(1) Optimization is often desirable after much of the contamination has been removed and local "hot spots" remain. At this point, subsurface VOC concentrations in soil and soil vapor at individual wells should be checked to determine which wells are responsible for most of the mass removal. Wells in areas that do not yield much mass can be taken "off-line" or operated to concentrate airflow on the more contaminated areas. Care must be taken during this analysis to ensure that adequate capture zones are maintained at sites where vapor emissions to the surface are important.

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(2) One problem encountered in shallow systems (less than 1.5 meters to the water table) or in soils with high proportions of silts and clays is the possibility of excess moisture in the treatment zone (due to upwelling) and subsequent introduction of water into the vacuum system. A cyclonic separator may be overloaded very quickly if water is entrained in the air stream which can in turn infuse vapor phase activated carbon with water, substantially lowering its sorptive capacity. This process often causes excessive system "down-times" and offgas treatment costs. This problem can be mitigated by improving moisture separation and/or actively pumping groundwater to counteract the upwelling in situ.

(3) A related problem is the requirement for large vacuums due to tight soils or a shallow water table. If the vacuum generated at the pump is greater than the elevation head of the water table, the pump will sometimes draw the water to the surface whether the site is flooded or not. Liquid-ring vacuum pumps capable of drawing 635 mm of mercury vacuum will pump water from depths of at least 6 meters.

*b. The second category of optimization is re-evaluating the existing remediation system and, if warranted, modifying it by adding or replacing SVE wells for example, or changing the vacuum blower to increase flow and applied vacuum, or changing a SVE system to a bioventing system. If the soil gas flows too directly from the surface to the SVE wells' screens without traveling horizontally enough to encounter all contaminated soil, a lower permeability surface cover may need to be installed. This re-evaluation should also include the assumed contamination situation which may differ based on information gathered during the on-going remediation.*

## **8-9. Troubleshooting**

There are several mechanical components to an SVE/BV system which are subject to operating problems. Many of these become apparent at start-up, but others appear later if the system is not properly maintained. These parts of the system will be considered in order of flow. Troubleshooting guides are also provided in Table 8-1, and the Remediation System Evaluation checklists, at <http://www.environmental.usace.army.mil/library/guide/rsechk/rsechk.html>.

*a. Filters.* The air from the well is usually filtered through two stages to prevent damage to the vacuum unit. Problems associated with the lead filter, which is often a cyclonic system to remove soil and water droplets, are primarily related to plugging of the drain line with mud. The second filter is usually a fine filter, which should be checked daily during initial SVE (and BV, if applicable) system operation to make sure it is not blocked.

*b. Vacuum pump.* As long as the pump is properly lubricated and the filters are working properly, the vacuum pump should not experience operating problems. Performance checks against the pump curve should be conducted regularly during start-up to make sure airflow and vacuum levels meet expectations. Also the amount of current (amps) drawn by the blower should be measured.

*c. Air treatment.* The operating problems associated with carbon systems are usually minimal as long as the air is filtered and dehumidified. The carbon exhaust should be monitored periodically to ensure that the air being discharged meets the requirements of the air permit. If a thermal oxidation system is used, the system itself will have maintenance needs, and again the exhaust will need monitoring. In operating incinerator units, care must be taken that the VOC concentration in the incoming stream from the wells is factored into the burner operation, and as the concentration is reduced, the incinerator is adjusted accordingly. Burners typically are self-regulating within a limited range of fuel-to-air ratios; the range is

termed a turn-down ratio. A typical turn-down ratio may be 20 to 1. The burner will require readjustment if, due to a decrease in influent air concentration, the change in fuel-to-air ratio exceeds the turn-down ratio. Refer to USACE guidance documents on offgas treatment methods.

*d. Control systems.* Operating problems with control systems may occur due to malfunction of electrical components (which usually requires a service call by the equipment supplier), damage to buried wiring by burrowing rodents, or by exposure of components to weather extremes for which they were not designed. Enclosing the control systems in a heated (or cooled) shed will prevent damage from exposure to temperature extremes.

## **8-10. OM&M Protocols**

Throughout the course of the remediation, the system O&M manual will consistently be one of the most useful documents associated with the project. The O&M manual should contain detailed descriptions of any and all activities pertaining to the SVE/BV system that could potentially take place. The manual should be written so that a technician unfamiliar with the site could follow the instructions and perform any OM&M activity properly. Since design changes are common during system installation, commissioning and start-up, the O&M manual and as-built drawings should be completed at this time; and updated as changes are made.

*a.* The following is a general outline of the topics to be covered in an O&M manual for a basic SVE system:

- I. Introduction
  - A. Purpose of the O&M Manual
  - B. Objectives of the Remediation System
  - C. Description of Facilities
  - D. Project Organization
  - E. Record-Keeping
- II. Description of System Components (*includes As-Built Diagrams*)
  - A. Well Configuration and Construction Detail
  - B. System Piping and Instrumentation
  - C. Vapor Collection System
  - D. Vapor Pretreatment System
  - E. Vapor Treatment System

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F. Ancillary Equipment

G. Controls

III. System O&M

A. Start-Up

B. Routine Operating Procedures

C. Troubleshooting

D. Changeover from SVE to BV (if applicable)

IV. Contingency Plan

A. Mechanical Contingencies

B. System Modifications

C. Criteria for Triggering Corrective Action

V. System Maintenance

A. Weekly/Monthly/Quarterly Inspections (*including log sheets*)

B. Routine Maintenance Procedures (*including log sheets*)

C. Consumables and Spare Parts Inventory

VI. Monitoring, Sampling, Analysis, and Reporting Documentation

A. Remediation Goals

B. Discharge Limits

C. Sampling and Analysis Schedule

D. Reporting

E. Quality Assurance / Quality Control

Appendix A - Health and Safety Plan

Appendix B - Standard Operating Procedures

Air Sampling

Water Sampling

Water Level Measurement

*b.* This outline is intended for a basic SVE system only. Similar procedures for bioventing and other technology options (see paragraph 3-2) should be included as necessary.

*c.* While the contents of most O&M manuals are by nature highly site-specific and very detailed, an example section on weekly inspections is presented below to inform the reader of the types of information that should be included in the O&M manual. The contents of the example section have been generalized and abridged to maintain conciseness. Much more detail would be included in an actual manual.

## Chapter 9 System Shutdown and Confirmation of Cleanup

### 9-1. Introduction

The attainment of agreed-upon conditions under which remediation activities may cease and the SVE/BV system may be decommissioned is the ultimate objective of the remediation effort. This requires a series of steps to demonstrate that the air being processed and the soil in the treatment area have met established criteria.

### 9-2. Shutdown Strategy

*a.* Federal and state regulatory media-specific cleanup requirements, voluntary cleanup requirements, or risk-based requirements established for the particular contaminant(s) to be remediated drive the shutdown of a remediation system. Site-specific cleanup objectives are usually established by the Federal and/or state agencies, if no generic cleanup levels exist. In many cases, the cleanup requirements are determined based on a need to protect the quality of the underlying ground water. As the initial step in determining the shutdown strategy, the design team must be familiar with all Federal and/or state soil cleanup objectives. Table 9-1 lists factors that may influence one to commence shutdown.

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**Table 9-1**  
**Possible Criteria to be Considered in Evaluating Shutdown of SVE/BV System**

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**Offgas Analysis** (Continuous and Pulse Venting - *MUST be considered in conjunction with other data*)

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- Total emissions or individual VOCs exiting blower exhaust are not evident.
  - Total emissions or individual VOCs exiting blower exhaust reach predetermined levels.
  - Total emissions or individual VOCs exiting blower exhaust reach asymptotic conditions and design deemed adequate.
  - No rebound is observed in influent concentrations upon system restart, following reasonable system shutdown period.
  - Operation costs greatly exceed value of continued vapor removal (operator's decision).
  - Pulse venting down time greatly exceeds pulse venting operation time (operator's decision).
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**Bioventing Respiration**

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- Oxygen respiration measurements performed within the area being remediated indicate declining contaminant degradability, relative to a background control.
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**Soil Gas Analysis** (from monitoring probes) *Recommended*

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- Soil gas constituents collected from remediation area reach asymptotic conditions and extraction and monitoring system designs deemed adequate.
  - Soil gas constituents collected from the remediation area indicate levels of nondetection with reasonable detection limits and concentrations.
  - Soil gas constituents collected from the remediation area indicate levels of residual mass that is no longer threat to ground water
  - Soil gas concentrations do not significantly rebound following reasonable system shutdown period
-

**Table 9-1**  
**Possible Criteria to be Considered in Evaluating Shutdown of SVE/BV System**

**Soil Sample Analysis** *Recommended, provided proper sampling strategy and methods used*

- Soil constituents collected from the area being remediated indicated levels below regulatory requirements or levels of nondetection (confirmatory analyses).
- If soil constituents collected from the area being remediated indicate levels above regulatory requirements, and operation times and cost have been exceeded, the operator may request a variance from the regulatory agency to accept remediated levels (refer to paragraph 9-5, Evaluation of Results).

*b.* Shutdown strategies can be based on:

- Soil sampling results compared to specific regulatory or risk-based soil concentration standards
- Soil gas sampling, compared to specific soil gas concentration standards
- Soil gas concentration rebound following shutdown for reasonable period (see Section 9-9 and Appendix F)
- For BV systems, attainment of low respiration rates

In all cases, the design of both the remediation and the monitoring system must be evaluated to ensure it is in accordance with good practice, as defined by this manual.

*c.* Shutdown strategies based on the need to protect ground water are becoming more common. In most cases, the removal of contaminant mass in the vadose zone must continue until the residual mass will not leach to the ground water in quantities that would cause exceedance of ground water quality standards. This typically is evaluated through the use of leaching models and the assumption that some mixing of the leachate and ground water occurs below the water table. The details of this mixing (i.e., thickness of mixing zone, etc.) are often the subject of debate. It is unrealistic to neglect this mixing, but it is not conservative to overestimate the thickness of the mixing zone in the absence of hydrogeologic data. The observed thickness of the ground water plume or the typical length of either monitoring well screens or production well screens may be a basis for the thickness of the mixing zone. The acceptable soil concentration may be determined through the modeling (DiGiulio et al., 1999), or, by assuming equilibrium between phases, an acceptable soil gas concentration can also be computed. At an Air Force Base in California, further analysis has been done to determine the acceptable soil remediation by SVE considering the cost of simultaneous ground water extraction. The evaluation considers the cost of removing additional mass through the SVE system, versus the additional cost for future ground water extraction accounting for the added leachate from the vadose zone if SVE is stopped. The operation of the SVE system would continue only if the reduction in the cost of future ground water extraction was more than the cost of the additional SVE. This requires the use of both vadose zone leaching and ground water contaminant transport models and is probably justified only on larger SVE sites where ground water is already impacted.

*d.* The USACE Remediation System Evaluation process can also be used to help identify when the system may be ready for shutdown or when enhancements may be necessary to reach remediation goals. Refer to the Soil Vapor Extraction Subsurface Performance checklist available at <http://www.environmental.usace.army.mil/library/guide/rsechk/rsechk.html>. The checklist guides the user in analysis of data to determine if the system has reached a limitation, if operation needs to be changed to

improve progress toward closure, if a change or addition of remediation technologies is warranted, or if the system can be closed.

### 9-3. Sampling and Analysis

*a.* To verify that cleanup criteria have been achieved, the sampling plan described in the SAP will be carried out. The sampling is likely to be more exhaustive both spatially and analytically than that used during routine monitoring. The DQOs will probably be more rigorous as at this stage the consequences of errors are more serious. It will be important when determining cleanup confirmation or compliance with ARARs to use sampling techniques that are consistent with those used at system start-up, so that comparisons between the two sets of data are meaningful. Quality Assurance/Quality Control (QA/QC) samples, such as field duplicates, equipment blanks, trip blanks, and split samples sent to the USACE QA laboratory, will be an important component of the sampling program. Adherence to standard operating procedures, including sample notation and chain-of-custody procedures, is critical at this juncture. Table 3-4 lists the topics covered in a SAP.

*b.* It is important to note that it is NOT appropriate to wait until sampling for "closure" to perform thorough sampling and analysis of key soil venting parameters. In order to operate the system optimally, it is critical to frequently monitor parameters such as extracted concentration and flows from individual wells, in-situ soil gas concentrations from vadose zone piezometers, and water table fluctuations. A more comprehensive list of routine sampling parameters is found in Chapters 7 and 8. In addition the RSE checklists describe a set of parameters that should be monitored periodically to ensure that the system is operating as intended. By maintaining a good database of the "routine" operational data, the practitioner is unlikely to be surprised by the results of the sampling and analyses described in this chapter.

*c. Analytical.* Definitive fixed-laboratory analyses are usually required at this stage. Use of standard analytical methods and reference materials to enhance comparability of data over time and across laboratories will make the comparison valid. An example of a reference material might be a sample of floating product from a monitoring well in the case of remediation of a gasoline release. An aliquot of this product would be analyzed every time a set of field samples was analyzed to indicate differences in analytical response. Completion of remediation will be documented by attainment of agreed-upon contaminant concentrations using agreed-upon sampling and analysis methodologies.

### 9-4. Typical Data Trends

Usually the most concentrated exhaust stream treated by an SVE system is encountered at the beginning of remediation. The typical data trend for vapor phase contaminant concentrations is steeply downward for two to three months, after which concentrations approach asymptotic levels. This is graphically depicted for six example sites in Figure 9-1. Some systems are operated intermittently (pulsed) to periodically permit the soil system to equilibrate and introduce additional VOC into the soil air to maximize vapor phase concentrations. This may make the air treatment system more efficient, particularly for catalytic combustion treatment systems (see paragraph 8-2).

*a.* If the data do not demonstrate an appreciable reduction in vapor phase contaminant concentrations over the first few months of operation, it is possible that NAPL is present and acting as a continuing source of VOC vapors.

*b.* Several data trends are commonly encountered in monitoring contaminant concentrations in soil, soil gas, and vent gas. Residual soil contamination (paragraph 2-3c(6)) decreases with venting time, and distillation effects are apparent from preferential evaporation of more volatile compounds, leaving heavier compounds behind. However, tracking residual contamination accurately requires analyzing a large number of samples because soil, being an unmixed medium, is heterogeneous. Analysis of residual contamination is usually limited to before venting, to determine starting concentrations, and after the venting operation is complete, to confirm that treatment goals have been met. (Analyses of residual contamination in soil samples are actually analyses of the residual plus aqueous plus vapor phase contaminants.)

*c.* SVE shutdown should not be considered in isolation at sites with underlying contaminated ground water. Concentrations of contaminants in ground water should also be monitored to determine the contribution of contaminants from the aqueous phase to the soil gas. A site contaminated with up to 55 mg/kg of PCE in soil was subjected to SVE to achieve a cleanup goal of 1 mg/kg. After 9 months, the PCE concentration in vent gas was less than 1 percent of its initial value. Soil gas concentrations met shutdown criteria, but soil sample analyses showed PCE concentrations of up to 15 mg/kg. It was found that groundwater was recontaminating the soil by capillary action and water table fluctuations. Bulk fluid movement during a period when the water table rose and fell evidently accelerated the mass transfer process from the saturated zone to the unsaturated zone. Solute was apparently transported up into the vadose zone during a water table rise, and then exposed to soil gas in the vadose zone following a drop in the water table and draining of soil near the capillary fringe. Under stagnant water table conditions, by contrast, the mass transfer process would tend to be diffusion limited and therefore four orders of magnitude slower than during a period of bulk fluid movement. A rough calculation showed that groundwater could have contributed 270 kg of the more than 325 kg of PCE that were removed by the SVE system (Urban 1992). By performing extensive simulations using the multi-phase flow model, T2VOC, Williams et al. (2000) have demonstrated a similar phenomenon at the Twin Cities Army Ammunitions Plant (TCAAP).

*d.* Air, being a mixed medium, is more economical than soil for monitoring the progress of SVE/BV operations. Vent gas concentrations can provide a gauge of mass removal from the whole soil volume affected by the SVE/BV system, while soil gas monitoring can resolve spatial variation in vapor phase contaminant concentrations. Monitoring of vapor phase compounds, including both VOCs and O<sub>2</sub>, CO<sub>2</sub> and methane in monitoring points will assist greatly in calibrating flow models and improving confidence in the results of the modeling. Another parameter which may be measured is tracer gas concentration at monitoring points after injection of the gas into a specified point. This permits estimation of flow velocities to assist in calibration of models and estimation of pore volume exchange rates across the site (USEPA, 1996).

*e.* BV is at times employed for treatment of soils contaminated with weathered fuels containing relatively heavy petroleum hydrocarbons. In such applications, soil concentrations have been observed to decline moderately fast at first, then the degradation rates decline slowly over time. Concurrent shutdown testing performed periodically indicated that oxygen uptake rates declined over time, signaling that most of the more biodegradable constituents had been consumed. A risk-based approach to viewing such data might argue that if the remaining constituents are so low in solubility and volatility that they are no longer bioavailable under operating conditions that are known to favor biological activity, they may no longer present a risk, provided that direct contact exposure routes can be prevented through appropriate administrative or containment measures (Smith et al. 1995).

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f. Hiller (1991) reviewed a number of full-scale SVE case histories and selected for analysis six well-documented successfully vented sites with TCE and/or PCE contamination which varied somewhat in geologic setting and initial contaminant concentrations. Vent gas PCE/TCE concentrations followed similar trends at the six sites, with an initial steep 80 to 90 percent decline lasting about 20 days, followed by a gradual asymptotic decrease to background concentrations. During this latter phase, concentrations were similar among sites, falling from 20 ppm or less to about 2 ppm in the final stages after 6 months. The data are shown in Figure 9-1. This was interpreted to reflect initial rapid evaporation of free product droplets, followed by a diffusion-controlled process of partitioning of contaminants previously dissolved in soil moisture into the gaseous phase and desorption from soil particles. However, sharp declines in extracted vapor concentrations do not always indicate that advective removal has ended. If only aggregate vapor concentrations are monitored (i.e., from a common header), then the behavior of each well is masked. Areas that contain high concentrations, but yield low air flowrates may be obscured by wells that yield higher flow rates. This emphasizes the importance of monitoring individual wells.

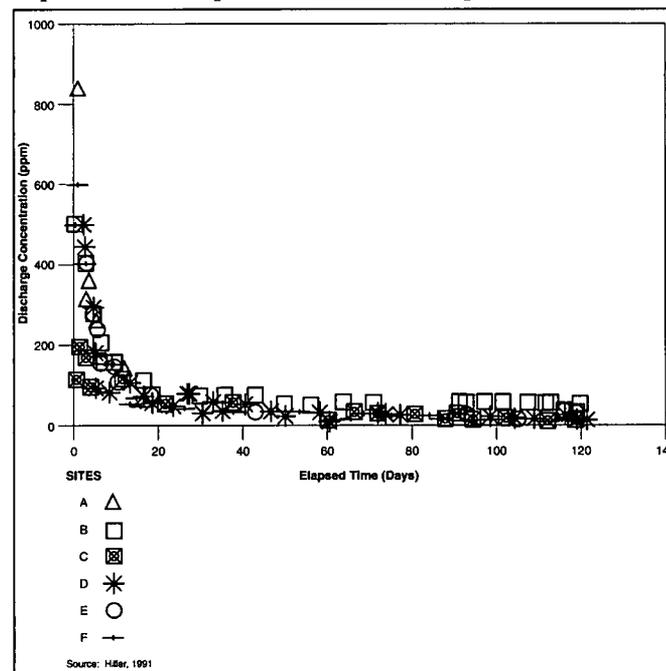


Figure 9-1 Vent Gas VOC Concentrations at Six Sites Over Time

## 9-5. Evaluation of Results

a. *Methods of evaluation for shutdown.* The results of the sampling and analyses described above must be carefully evaluated before deciding that the system is ready to be shut down. Typically, the criteria for determining when the system can be shut down include one or more of the following:

- Total amount of contaminant removed.
- Residual soil concentrations.
- Extraction well(s) vapor concentrations and composition.
- Soil gas contaminant concentrations and composition in monitoring points.

*b. Mass Removed.* Given the often highly uncertain quantity of material released or mass present in the subsurface prior to remediation, the comparison of the mass removed to the mass initially present is a poor criteria for shutdown. At some sites, such as a Superfund site in Arizona, more mass was removed in the pilot test than was estimated during the remedial investigation to be present at the entire site, and mass removal was still high at the end of the test.

*c. Target soil concentrations.* As discussed above, many states' target cleanup levels, especially for petroleum hydrocarbons, ultimately limit the residual concentrations of contaminants in the soil. Since soil sampling is both costly and potentially disruptive, the site operator will want to be quite certain that the soil samples will show that the cleanup levels have been attained before they are collected. For this reason, the shutdown sampling is typically conducted in stages, whereby the attainment of one criterion will trigger the next level of testing, and so on, until achievement of cleanup levels is confirmed. For example, the first criterion might be the attainment of a target vapor concentration in monitoring points, based on a correlation between extracted vapor and soil concentrations. If this target were met, the system might be shut down for a number of days, after which the in-situ soil gas concentrations and composition would be analyzed. If the soil gas results following shut down met target levels, only then would actual soil samples be collected. Finally, the results of the soil analyses would be compared with the actual cleanup levels for residual soils. At this point, the system might be shut down, but often the equipment will remain in place for some period of time in the event that future confirmatory samples show that concentrations have risen above cleanup levels again, in which case system operation would be resumed. The use of soil sampling for confirmation of cleanup and system shutdown must consider carefully the heterogeneous distribution of soil concentrations at a site and the uncertainties associated with sampling soils for VOCs. Soil sampling to confirm cleanup requires the use of statistically based sampling strategies to quantify the certainty of achieving goals (USEPA, 1989e). The current SW-846 method 5035 is strongly recommended for sampling soils for VOCs.

*d. Extracted Vapor Concentrations and Composition.*

(1) In many cases, the SVE system is operated until the concentrations in the extracted vapors either drop to non-detectable levels or to some asymptotic (but low) level. There are some caveats to this method, however. First, although the decrease of concentrations in the extracted vapor is an indication of the effectiveness of the system, it is certainly not conclusive evidence that the concentrations in the soil have decreased proportionally. Johnson, Kemblowski, and Colthart (1990b) list other potential reasons for decreases in vapor concentrations:

- Water table upwelling.
- Soil drying.
- Diffusion constraints.
- Short-circuiting.

Use of the concentrations in the influent or from an individual extraction well for shutdown decisions, in the absence of other data, is also prone to errors due to the large component of relatively clean flow to many extraction wells that often enters the subsurface near the well. This large component of the flow travels through the zones near the well that are thoroughly flushed after some operation compared to soils at greater distances from the vent. It is quite easy to design an SVE system that reaches low influent concentrations while still leaving a significant quantity of mass in the soils, especially near stagnation

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zones. Because of this uncertainty, the composition of the extracted vapors is usually monitored as well as the concentrations.

(2) Holbrook et al. (1998) explain that if the composition of the extracted gas stream from an SVE system at a petroleum fuel site reflects higher and higher boiling compounds, then the extraction system can be considered to have successfully remediated the site relative to the more volatile compounds. The system may then be focussed on bioventing the less volatile components. This approach is applicable to sites where the SVE system is affecting all of the contaminated soil. If there are pockets of contamination that are subject to rate-limited mass transfer and are not being remediated by advective flow, or are only slowly being remediated, then changes in extracted gas composition will NOT allow evaluation of how close the system is to achieving specific cleanup goals. Rather, compositional analysis provides insight into how well the system is performing relative to its ability to treat the part of the problem it can "reach" advectively.

*e. Rebound of concentrations in extracted vapors.* An alternate method of applying this approach involves the use of pulse extraction, where an area is alternately subjected to a vacuum and then allowed to return to "atmospheric" conditions. This method may be employed by using the same vacuum pump to treat two (or more) areas of a site, and cycling over two-week (or other) operating pulse times. When an area is brought back under vacuum, the initial concentrations of VOC are measured in the extracted airstream and compared with the initial readings for previous operating cycles. The initial concentrations at each cycle are plotted versus time to demonstrate a drop in the "equilibrium" soil air concentrations. An example of this graph is shown in Figure 9-1. When the initial cycle concentration approaches zero for the compounds of concern, consideration should be given to entering the shutdown phase. Further information regarding rebound testing is provided in section 9-9 and Appendix F. The use of rebound testing based only on extracted vapors is subject to the same uncertainties and caveats discussed above.

*f. Soil gas concentrations in monitoring points.* Soil gas concentration and composition in strategically placed monitoring probes can be the most effective indicators of the progress toward cleanup. As stated in Chapter 5, monitoring points must be installed in areas that will be the most difficult to remediate and placed in geologically representative strata. If soil gas concentrations decline in areas between extraction (and injection) wells where air throughput or oxygen delivery is the least effective, then the system is probably being effective. Soil gas concentrations are less expensive to collect, and generally represent more integrated (i.e., from a larger area) data. Adequate purging must be conducted before sampling, however. Although soil gas sampling conducted during remediation is often done, care must be taken to not allow clean air entry into the monitoring probe before purging since the subsurface is usually under vacuum relative to the atmosphere. Sampling conducted during remediation also represents the dynamic condition where clean air is being drawn into the treatment areas, and the diffusion-driven release of contaminant vapors is diluted by the entry of clean air. Soil gas sampling of monitoring points following temporary shutdown is a more reliable means to assess progress. Some rebound of soil gas concentrations in monitoring points is likely following shutdown and rebound may take weeks. When significant rebound is not observed, available mass has probably been removed. Remaining mass is likely in low-permeability zones that are unlikely to allow significant leaching of mass to occur. If regulatory requirements permit, soil gas concentrations from monitoring points are the preferred data to use for establishing clean closure.

*g.* For BV systems, the focus of evaluation of treatment progress should be on contaminant degradability. Oxygen respiration measurements conducted routinely (e.g., quarterly) should be used as an indicator of when system shutdown should be considered. Only when respiration rates drop to background levels (i.e., those observed in uncontaminated soil of the same type) would confirmatory soil core samples

be collected and analyzed for specific constituents of interest to verify contaminant removal. Leeson and Hincee (1995) indicate that respiration rates below 1 % O<sub>2</sub>/day represent background. If in situ respiration starts significantly above 1%/day, and then drops below this value, it is indicative of a halt to biological treatment. This halt may be due to a variety of factors, including:

- Changes in soil moisture (e.g., raised water table) occluding the pore in contaminated zone, preventing the delivery of oxygen. This can be investigated by observing changes in soil moisture and the local water table.
- Reduction in available macro or micro-nutrients, limiting biological activity. In some instances, bacterial populations "run-out" of nutrients such as phosphate necessary for respiration, even though there are adequate sources of carbon (i.e., contaminant) and oxygen. In situ addition of nutrients, or collection of soil samples for bench scale tests can elucidate these limitations.
- Reduction in available carbon (i.e., contaminant) for respiration. Rebound testing (see paragraph 9-9) can help evaluate this possibility. This result may help make the case for site closure.

#### 9-6. System Shutdown Checklist

A system can be automatically or manually shut down to minimize hazards and aid in decontamination of equipment and areas of the project. There are several reasons for shutting down a system:

- There may be a power loss at the site.
- Equipment failure may initiate shutdown in the control systems.
- The control systems may identify an operating condition that warrants shutdown.
- A system may be shut down for maintenance.
- Evaluating remedial progress by performing rebound tests.
- Remediation may be complete.

*a. Emergency shutdown.* If the system is automatically shut down, an operator should be called to check the system. Depending on the configuration of the system, there are several observations and notes an operator should make. If a control system includes a FIRST OUT indication (an indicator panel with lights to identify the failure), the operator is informed of the reason for the shutdown; however, it is expensive to include FIRST OUT indication for all possible influences on a system. If failure identifications are not included, the operator should check the unit for broken equipment, piping, hoses, or ducts. Accumulated liquids should be checked and stored properly. Check for electrical power failure. If there are no apparent failures or reasons for shutdown, the system can be restarted and the operator can watch or even listen for causes of a failure.

*b. Maintenance shutdown.* If the process system is intentionally shut down, there are subsystems that should be checked. Decontamination of the system can lessen exposure problems during maintenance and dismantling of equipment. Steps include:

- Remove liquids from collection points.
- Isolate extraction well(s) and draw clean air through the entire system.
- Shut down vacuum pump(s) or extraction blower(s).

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- Close isolation valves.
- Disconnect electrical power to equipment.
- Log the event.

Depending on the reason(s) for shutting down the system, decontamination procedures could be more stringent.

c. If the operator believes that the site is approaching "clean" or if there is interest in trying to understand and quantify the extent of rate-limited mass transfer (e.g., diffusion from low permeability strata), then a rebound test may be performed. Shutdown for rebound tests should proceed according to the shutdown procedures described in the site specific O&M manual. However, prior to shutdown for rebound testing, it is important to collect a complete set of system performance data. This data should include:

- Flow rate and concentration(s) from each extraction well and vacuum applied to each well (for SVE systems)
- Injection rates to each injection well (if applicable).
- Soil gas concentrations of site specific VOCs, gaseous O<sub>2</sub>, CO<sub>2</sub>, and methane from both monitoring points and extraction wells.
- Vacuum/pressure distribution within the treatment area, e.g., vacuum measurements at vadose zone monitoring points and nearby water table wells.
- Groundwater elevations (if the contaminated zone is near or within the capillary fringe) in the treatment zone, including degree of upwelling at extraction points.

The extracted gas concentrations and flow rates may have to be collected multiple times if a model is used to quantify diffusion limited mass transfer (see paragraph 9-9). Groundwater and soil VOC concentrations are not particularly useful to evaluate rebound.

d. *Remediation shutdown.* In the later phases of remediation, extraction wells may be shut down one at a time. A wellhead valve can be included to isolate each well when cleanup criteria are met. The system should be designed to operate at reduced airflow rates without jeopardizing the performance of the system. Final shutdown of the system should follow the same activities as those for maintenance shutdown. Decontamination procedures should be followed to minimize loss of contaminated materials to surrounding areas.

### 9-7. Closure Report

Once remediation has been completed, a closure report/construction documentation report should be prepared to verify and document the activities and results of the remediation project. It should be noted that prior to the preparation of the closure report, the design team must determine if the acting regulatory agency has a specific format to follow and/or additional forms to be filled out.

### 9-8. Long-Term Monitoring Requirements

Long-term monitoring requirements following system shutdown, if any, will be defined in the SAP and perhaps modified pursuant to data collected during the operation of the system. Typically, analyses will be

for selected target compounds rather than the full suite of site compounds. Care must be taken to collect and analyze the samples consistently with the collection and analysis procedures used during prior phases of the project to maximize comparability. The SAP should include provisions for resampling should an unusual positive result be found during this stage. The data should continue to be entered into the database if one had been implemented.

### 9-9. Rebound

As previously described, the rate of contaminant removal by soil venting is generally fast during early phases of operation and then becomes progressively slower until it approaches a relatively low value. When a soil venting system is turned off and then on again, there is generally a spike in the rate of contaminant removal, as depicted in Figure 9-2. This phenomenon is usually described as *rebound*, that is the concentrations of the contaminants rebound toward their initial higher levels after soil venting has ceased for some period. Rebound of vapor concentrations implies that rate-limited mass transfer is occurring during soil venting. For example, if air extraction rates exceed the rate of diffusive mass transfer from within the pore water to the air-water interface and then into the flowing air stream, contaminant concentrations in the extracted air can diminish without removing all of the contaminant from the pore water. When extraction stops, the diffusion process continues and eventually the concentration(s) within the soil pores that are most conductive to air begin to rise. If a soil gas sample is collected or extraction begins again, then the contaminant concentrations will have "rebounded". Rebound will be observed whenever air extraction occurs faster than the rate of contaminant diffusion from some sequestered location. Contaminants can be considered sequestered if they reside outside of the air-filled pores that conduct the majority of the air that flows to the extraction well.

*a. What is the significance of rebound?* At many sites, the objective of soil venting is to reduce soil contaminant concentrations to below a specific value. Those portions of the subsurface that can readily be swept by air that flows due to soil venting may reach these target values. However, if concentrations are observed to rebound, then there is most likely soil where contaminant concentrations have not been appreciably reduced to target clean-up levels. Thus, even at sites where substantial contaminant mass is removed by soil venting, this "sequestered" contamination can often cause the site to fail to meet cleanup objectives.

*b. How is rebound measured and assessed?* Rebound in the simplest sense is observed when a system is shut down for a time, and then vapor phase concentrations are observed to rise in the treatment area. This phenomenon is observed at most sites, however, site specific conditions such as soil stratigraphy, moisture content, and historical pattern of contamination cause the rate at which contaminant concentrations rebound to vary dramatically from site to site. There is rarely a systematic approach applied for measuring rebound or for evaluating the rate and extent of concentration rebound. Instead, rebound tests are often used to qualitatively evaluate the progress of remediation, or sometimes quantitatively to compare the rebounded concentration at some designated time to a specified "standard". However, a properly executed rebound test can provide much greater insight into the status of remediation. Appendix F provides a detailed approach for performing rebound tests and for interpreting the data collected before and during the test. In addition, Appendix F provides the mathematical framework that is the basis of rebound data evaluation, as well as the basis for modeling SVE/BV cleanup rates and predicting remediation endpoints and timeframes.

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*c. Estimating the Impact of Diffusion Limitations on Remediation Timeframes*

(1) By measuring rebound rates and using a simple analytical model (Brusseau 1996) some practitioners are able to estimate the impact of rate-limited mass transport on remediation timeframes. Praxis Environmental Technologies, Inc. developer of the PneuLog™ tool, reports that mass transfer constraints, order-of-magnitude total mass, and time to cleanup can be estimated from historical concentration data and rebound test data. Figure 9-2 shows data collected using a PneuLog™ device to vertically profile extracted concentrations and flow rates in a single SVE well during a rebound test. SVE was performed at this site for 12 days, then paused for four days, and then reinitiated at the same flow rates as before. The data show the characteristic rebound in extracted vapor concentrations that is seen in most SVE systems. At this site, the rebound in TCE concentration is presumably due to diffusion from a less permeable zone into the pathways that transmit most of the air to the extraction well. After the pause, a rebound in the extracted vapor concentration of almost 10 percent was observed.

(2) Figure 9-2 also includes a plot of the results of Brusseau's model, with best-fit parameters, and displays a close match with the measured concentration decay and rebound. The model has been developed in the academic literature (Brusseau 1996) but is used infrequently in field practice because the proper data are not collected or practitioners are not familiar with the model.

The basic simplifying assumptions in the model are:

- soils are categorized as two-domain, i.e., permeable to air flow (mobile) or not (immobile); and
- the early flushing rate of the mobile zone by clean air is rapid enough to justify averaging the contaminant concentration in the mobile zone.

(3) Typical SVE flow rates flush the mobile zone with clean air every few days justifying the averaging assumption. Most sites readily meet the conceptual model of mobile and immobile zones for air movement during SVE. A third category of low flow zones (e.g., silts) can be added if sufficient site data exist. Air moves through the mobile soils and contaminants must diffuse out of immobile zones before being extracted. The form of the equation describing the vapor concentration in the mobile zone (assumed equal to the extracted concentration) is roughly:

$C_{mobile}$  is a function of [Contribution of Mobile Zone] + [Contribution of Immobile Zone]

or

$$C_{mobile} = f(\Theta_1 e^{r_1 t} + \Theta_2 e^{r_2 t}) \quad (9-1)$$

where:

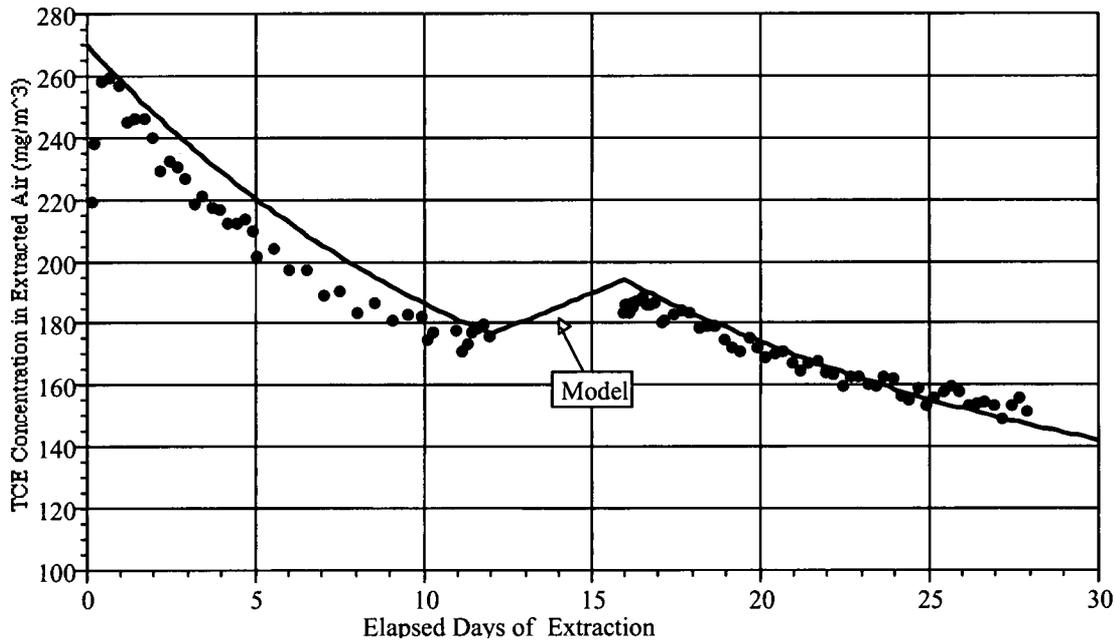
$\Theta_1$  = an advective decay constant

$\Theta_2$  = a diffusive decay constant

$r_1$  = a function of air residence time within the soil pores

$r_2$  = a function of the compound's diffusivity in the rate - limiting soil type

$t$  = elapsed soil venting time



**Figure 9-2. Measured and Modeled Extracted TCE Concentrations during SVE (Figure Provided Courtesy of Praxis Environmental Technologies, Inc. Burlingame, CA)**

(a) The first exponential term is dominated by the timescale associated with the total volume of contaminated soil and the air extraction rate. This is a convective process. The second term is dominated by diffusion from the immobile zone into the mobile zone. For the rebound test, when extraction is zero, the magnitude of  $r_1$  becomes equivalent to that of  $r_2$  because all processes are then diffusion dominated. Therefore, the rebound concentration yields an estimate for the diffusion rate. Additional exponential terms can be added if other sources can be quantified (e.g., off-gassing from contaminated groundwater or evaporation of a NAPL) or if low flow zones such as silts make significant contributions. As SVE progresses at a site, the model coefficients can easily be revised. The immobile fraction of the soil becomes the dominant parameter in reaching cleanup and the longer SVE operates the more accurate this parameter estimate becomes. In the past, sites were often described solely by the convective exponential term and ignored a determination of the longer transient associated with the diffusive exponential term. Neglecting the contribution of the immobile zone resulted in vastly underestimating the time to reach a specified cleanup goal and the total mass of contaminant at the site.

(b) Fitting the multi-region model to the extracted concentration will also allow mass estimates to be calculated. The cumulative mass removed will be determined by integrating the extracted concentration represented by equation (7-1) over time from zero to the present time and multiplying by the extraction rate:

$$\text{Mass Removed} = \int_{t'=0}^t Q(t') C_{mobile}(t') dt' \quad (9-2)$$

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where

$Q$  = the air extraction rate ( $L^3/T$ )

$t'$  = elapsed SVE time

$C_{mobile}$  = extracted concentration

The extraction rate  $Q$  is usually constant over specified periods making the integration straightforward. An order-of-magnitude estimate for the total initial mass will be obtained by letting the integration extend to infinity.

## Chapter 10 Cost Estimating

### 10-1. Introduction

This chapter discusses considerations in estimating costs of SVE/BV systems.

### 10-2. Cost Estimating Strategy

The strategy and general approach to cost estimating for SVE/BV remediation are presented below.

*a. Establish the estimate type, goal, and accuracy.* Cost estimates should be prepared for various stages over the life of a remediation project. As more information is obtained about site conditions and proposed solutions, cost estimates typically become more precise and more detailed. Types of remedial action cost estimates are explained in ER 1110-3-1301 and are categorized as follows:

- (1) Preliminary Budget Estimate.
- (2) Feasibility Study (FS) Comparison Estimate.
- (3) Record of Decision (ROD) Estimate.
- (4) Current Working Estimate (CWE).
- (5) Government Estimate (G.E.).

Along with each of these cost estimates, the engineer must document assumptions used in preparing the estimate, provide an assessment of the accuracy of the costs, and provide a statement of limitations.

*b. Separate estimate into different categories.* Different categories of costs in estimates include site work, capital costs, nonconstruction costs (such as overheads, contingencies, and other markups), operations, 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, which require little or no equipment replacement. The Remedial Action Work Breakdown Structure (RA-WBS) and the Operations and Maintenance WBS provide standard structures for categorizing and reporting costs. The WBS is available at <http://www.environmental.usace.army.mil/info/technical/cost/costtool/costtool.html>.

*c. List cost components.* A list of cost components should be prepared. Components common to SVE/BV remediation are discussed throughout this manual and are listed in paragraph 10-4.

*d. Obtain cost information.* Cost information can be obtained from various cost data sources, including vendor quotes, cost estimating manuals, former actual remediation projects, and literature searches. Experienced cost engineers maintain files on former price quotes for common components. Prices should be obtained from several sources whenever possible. The cost engineer must be aware of exactly what is included in unit prices and document this information in the estimate. Software programs, such as RACER, can also be used to obtain cost information and develop cost estimates. More information on RACER can be found at the web site listed in paragraph *b.* above.

*e. Cost data analysis.* 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. 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 manual; however, the cost engineer should be familiar with the following terms and concepts:

- Net present worth analysis.
- Rate of return method.
- Capitalized cost method.
- 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 alternative analysis.

*f. Prepare assumptions and limitations.* Often the assumptions and limitations are of as much importance as the estimate itself. Examples of limitations are:

- Estimates are based on limited data, such as limited characterization or design information.
- Assumptions regarding the means and method of construction have been made.
- Prices of materials and labor fluctuate.
- Regulatory decisions are often unpredictable.

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.

### **10-3. Cost Estimating Approaches**

The cost engineer must ensure that costs are based on the appropriate operating SVE/BV system. Operating costs can vary depending on the type and/or configuration of the SVE/BV system used. 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.

#### 10-4. Cost Estimating Checklist

A suggested cost estimating checklist is provided in Table 10-1. This list includes most major SVE system cost components and has been divided into the following six categories: (a) Pilot Studies, (b) Site Work, (c) Treatment System Capital Components, (d) Nonconstruction, (e) Annual Operation and Maintenance, and (f) 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.

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**Table 10-1. Suggested Cost Estimating Checklist**

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##### **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
- Onsite Labor to Conduct the Pilot Study
- Laboratory Analysis
- Data Validation and Interpretation
- Report Writing
  - QAPP
  - HASP
  - Contingency Plan
  - Air Monitoring Plan
  - Groundwater Monitoring Plan

##### **Site Work**

- SVE/BV Well and Piezometer Installation
  - Drilling
  - Materials
- SVE/BV Trench Installation
  - Earthmoving Equipment and Operator
  - Sand, Gravel, and Clean Fill
  - Geotextile Fabric
  - Soil Disposal
- Site Clearing
- Foundation or Pad
- Manholes
- Below-Ground Piping
- Below-Ground Electrical
- Surface Cover
- Building Construction

(Sheet 1 of 3)

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**Table 10-1. (Continued)****Treatment System Capital Components**

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**Major Components**

Air/Water Separator  
Condensate Drop-Out Tank  
Blower  
Silencers  
Air Filters  
Carbon Vessels  
Fume Incinerator  
    Burner  
    Catalyst  
    Heat Exchanger  
VOC Monitor  
O<sub>2</sub>/CO<sub>2</sub> Monitor

**Minor Components**

Piping  
Valves  
Gauges - Pressure, Temperature, and Flow  
Electrical Controls and Wiring  
Switches  
Sampling Ports  
Mounting Hardware  
Painting  
Lighting  
Fire Extinguisher

**Nonconstruction**

Design  
Permitting  
Construction Management Supervision  
Fees  
Contingency  
Start-Up

**Annual Operation and Maintenance (annualized for Net Present Worth)**

Treatment System Monitoring and Sampling  
Environmental Sampling  
Laboratory Analysis  
Electricity  
Fuel for Heating or Fume Incinerator  
Carbon Replacement  
    Material  
    Labor  
    Disposal  
Equipment Replacement  
Labor for Maintenance  
Condensate Disposal  
Performance Evaluation and Optimization  
Reporting  
Regulatory Interactions

(Sheet 2 of 3)

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**Table 10-1. (Concluded)**

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**Shutdown**

Final Sampling

Regulatory Interactions

Equipment Disassembly and Demobilization

Demolition

Salvage Value Credit (Negative Cost)

Reporting

(Sheet 3 of 3)

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## Chapter 11 Other Considerations

### 11-1. Regulatory Issues

*a.* State and Federal regulatory requirements should be identified by the designer prior to design, construction, or operation of an SVE/BV system. Many states have regulations governing any air discharge; therefore, a permit may have to be obtained before beginning pilot testing or operation. State permits may be required for well drilling and construction, even when the well does not encounter groundwater. Federal requirements promulgated by the Resource Conservation and Recovery Act (RCRA) include regulations for the handling and disposal of condensate and other residuals, such as investigation-derived wastes. Sites handled under the Federal Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) program would have to adhere to the CERCLA process as well as meet all Applicable, Relevant and Appropriate Requirements (ARARs) of other Federal and state regulations and laws.

*b.* The Federal Clean Air Act (CAA) provides transfer of authority to implement and enforce the majority of CAA requirements to individual states. It is therefore important that design personnel become familiar with state air quality requirements for the state in which the system will be constructed. Many states have specified emission control equipment and/or specific emission limits for sources emitting VOCs and other hazardous air pollutants. State requirements are frequently more stringent than are Federal requirements, and many states have regulations and standards that are not addressed under Federal regulations. Prior to selecting emission control equipment, project designers should research state requirements.

### 11-2. Patent Issues

A number of patents have been issued that relate to technologies covered in this manual. Readers are advised to consider the ramifications of these patents on their site activities. Contact Office of Counsel for guidance on addressing this issue. The following list presents some of the pertinent patents, but it is not intended to represent a complete patent search.

*a.* 4,183,407; 4,323,122.

Soil Vent Technologies, Duane Knopik - An exhaust system and process for removing contaminant vapors from contaminated underground areas. Also, a system and method for recovering organic liquid which has settled on the water table in underground areas (see paragraph 1-4f). (U.S. District Court 1994).

*b.* 4,593,760.

James J. Malot - Process for removing volatile liquid by applying a vacuum to a vertical conduit in a borehole. Process removes air and vapors. Process also employs injection of air.

*c.* 4,660,639.

James J. Malot - Process for removing volatile liquid by applying a vacuum to a vertical conduit in a borehole. Process removes fluids and employs liquid pumping with vacuum.

*d.* 4,730,672.

Mid West Water Resources - Process for improving airflow by using an impervious barrier on the ground surface.

*e.* 4,890,673.

Mid West Water Resources - Method of improving airflow in the aquifer by using an impervious barrier on the ground surface.

*f.* 4,919,570.

Mid West Water Resources - A treatment apparatus involving multiple cyclically connected vessels. Vessels are sealed and attached to both a pumping and a treatment station.

*g.* 4,945,988.

Mid West Water Resources - Process of aiding contaminant recovery by injecting substantially oxygen-free air into the aquifer to retard the formation of aerobic bacteria; and injecting oxygen-rich air into the vadose zone to stimulate bacterial growth.

*h.* 5,050,677.

Mid West Water Resources - Process of either injecting air or withdrawing fluids from a conduit inserted into a borehole. The borehole is filled with high porosity material and capped.

*i.* Patent pending.

Mid West Water Resources - A method of controlling airflow pathways to induce airflow into zones which have no net airflow, by rotating the orientation of airflow. This patent was shown as pending over 5 years ago but is not shown in records of the US Patent Office.

*j.* 4,765,902.

Chevron Research Co. - Process for biodegrading hydrocarbons by drawing oxygen into a contaminated zone through a vertical fluid-permeable conduit, and monitoring oxygen, hydrocarbon, and carbon dioxide.

*k.* 4,832,122.

U.S. Dept. of Energy - A system for removing volatile contaminants from a subsurface plume of contamination comprising two sets of wells, a well for injecting a fluid into a saturated zone on one side of the plume, and an extracting well for collecting the fluid (gas and/or liquid) together with volatilized contaminants from the plume on the other side of the plume.

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*l.* 5,018,576.

University of California - Process for in situ decontamination of subsurface soil and groundwater by injection of steam into injection wells and withdrawal of liquids and vapors from extraction wells under subatmospheric pressure.

*m.* 5,050,676; 5,197,541.

Xerox Corporation - A process and apparatus for two-phase vacuum extraction of contaminants from the ground involves vacuum withdrawal of liquid and gaseous phases as a common stream, separation of the liquid and gaseous phases, and subsequent treatment of the separated liquids and gases to produce clean effluents. Two-phase vacuum extraction employs a single vacuum-generating device to remove contaminants in both the liquid stream and soil gases through a single well casing.

*n.* 5,172,764.

Xerox Corporation - Process and apparatus for groundwater extraction using a high vacuum process.

*o.* 5,221,159.

Environmental Improvement Technologies - Subsurface contaminant remediation, biodegradation, and extraction methods and apparatuses.

*p.* 5,279,740.

AT&T Bell Laboratories - Process for in situ decontamination of subsurface soil and groundwater by simultaneous injection of steam and nutrients into wells to enhance the growth of hydrocarbon-degrading biota for the purpose of producing compounds of greater mobility, and withdrawal of liquids and vapors from extraction wells.

*q.* Patent challenges.

“Two of these patents, those held by James J. Malot, have been defended. Initially, when the patents were issued the most common response was to cite several API studies (API 1980a; API 1980b) which significantly predated the Malot filings. However, Malot resubmitted this prior art to the patent office which reissued the 4,660,639 patent with the examiner claiming that the API literature covered only vapor removal, whereas Malot’s patent covered vapor and liquid removal simultaneously and from the same borehole. The heart of the controversy is whether or not the practice of vapor extraction predates the patents, and was, because of accepted practice, obvious technology to those schooled in the art. An important difference between much of the earlier work and Malot’s patent is that earlier work used low vacuum, whereas Malot’s system uses high vacuum” (Brown 1992). In a recent U.S. District Court decision, the judge invalidated claim 8, the central claim of the Malot patent No. 4,660,639, citing prior art (U.S. District Court 1994). Users are advised to consult the Office of Counsel for specific patent guidance.

### 11-3. Safety

Appropriate safety and health procedures shall be developed by the design team and followed for all aspects of SVE/BV installation and operation. Both the contractor and USACE personnel shall comply with all applicable 29 CFR 1910/29 CFR 1926 standards, giving special attention to 29 CFR 1910.120(b)/29 CFR 1926.65(b) requirements for a Contractor Safety and Health Program (SHP) and a Site-specific Safety and Health Plan (SSHP). The SSHP shall be developed also in accordance with Appendix B, ER 385-1-92. In conjunction with Federal regulation compliance, the contractor and USACE personnel shall comply with all pertinent provisions of USACE Safety and Health Requirements Manual, EM 385-1-1. Where there is overlap between the Federal requirements and USACE requirements, the contractor shall adhere to the most protective. In certain instances, state and/or local safety and health requirements may also be applicable. In those instances, the contractor shall be responsible for the knowledge of and compliance with the state and/or local requirements. In all cases, *the most protective* regulations shall apply.

*a.* The SSHP monitoring provisions shall include work area monitoring for the presence of explosive or toxic gases which may endanger workers and, otherwise, for the presence of any oxygen-depleting or oxygen-displacing gases. The explosive gas/inert gas monitoring is in addition to the site-specific, worker exposure monitoring to be identified in the SSHP for the project. (Cases have been reported where VOC soil vapor, while within acceptable concentrations below the applicable LELs, contained such high levels of carbon dioxide that the oxygen content of the worker breathing air was reduced to unsafe levels. In another instance, an explosion reportedly occurred at a SVE site because of a failure to properly monitor for the explosive gases.)

*b.* The SSHP provisions shall give special consideration to other safety and health issues unique to SVE/BV. Refer to EM 1110-1-4007, Safety and Health Aspects of HTRW Remediation Technologies, Chapter 7, Soil Vapor Extraction (In Situ), Bioventing, Biodegradation, Thermally Enhanced Soil Vapor Extraction, for a discussion of health and safety issues of SVE and bioventing and a hazard analysis of the technology.

### 11-4. Contracting

*a. Coordination and general issues.* The design team must coordinate early in the SVE/BV project with the Contracting staff. This allows the nature of the SVE/BV process to be considered in developing a "project execution plan," including contract acquisition. Since SVE/BV often includes significant costs for equipment rental and O&M relative to capital costs, these factors can make a difference in the decisions about contracting the SVE/BV project. The project execution, planning, and contracting strategy may also affect the design. For example, if the duration of the work would be long, and it is decided to include only limited O&M in the initial contract, specified equipment may need to be easily modified by a separate O&M contractor to adjust to a change from SVE to BV at a later time. If the duration is likely to be short and a service-type contracting mechanism is used, a performance specification to be met by a packaged SVE/BV unit rented from a supplier may be preferred. Finally, payment for operation of an SVE/BV system can be based on various parameters including simple time, time of successful operations (based on hours of blower operations) and diligent repair, or mass of contaminants removed or destroyed.

*b. Design/Build Model of SVE Remediation.* An alternate approach to SVE/BV design that should be considered on a project-by-project basis is predicated on the phased implementation concepts described in

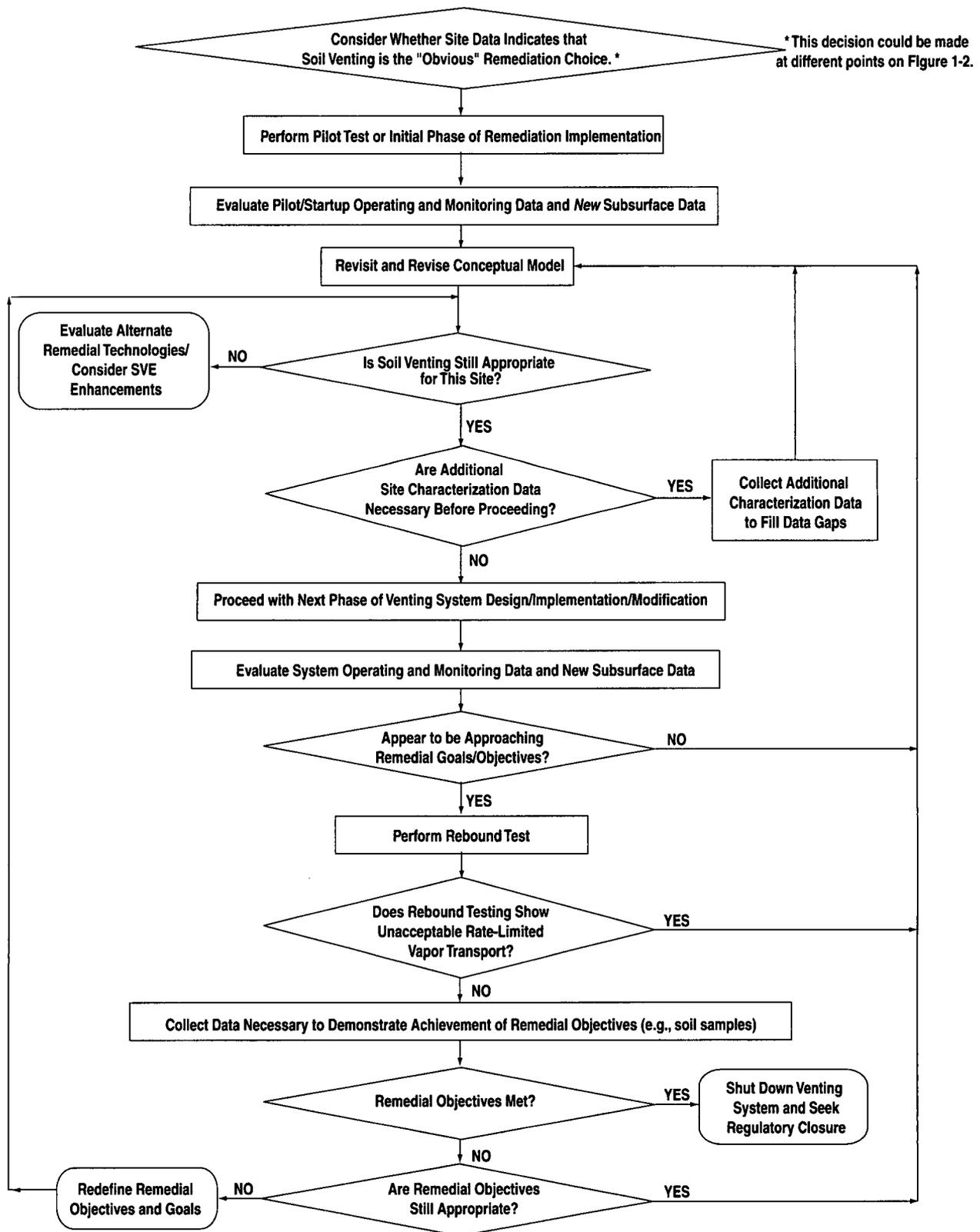
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Chapter 3, section 3-3b. This phased approach is sometimes referred to as a design/build model of remediation. The flowchart shown in Figure 11-1 describes the phased remediation process in which soil venting as the remediation approach is first validated, then implemented, and finally optimized in a series of phases. Throughout these phases, soil venting system operational data and subsurface monitoring data are used to frequently re-visit and improve the conceptual model of the site. Indeed, these data are also used to frequently check and validate the continued applicability of soil venting as a remedial process. As the understanding of the site improves, even the remedial objectives for the site must be revisited and confirmed.

(1) The phases illustrated in the Figure 11-1 flowchart include RI-like data collection and interpretation such as described in Chapter 3, in the midst of installing and operating pilot or full-scale SVE/BV systems. These phases are not further elaborated upon here, however, it must be re-emphasized that it is wrong to completely "decouple" investigation and remediation activities. All site activities that involve the subsurface must be viewed as opportunities to improve the understanding of the site and to update the conceptual site model. With that understanding, the remaining discussion in this precept describes the interaction of remediation implementation activities and design.

(2) Design/Build is a concept that acknowledges that the design basis for in situ remediation systems is never as solid and unchanging as the basis for other, more traditional engineering designs. Design/Build SVE projects maintain the active participation of the design team throughout the remediation process. By involving the designer(s) in the implementation process, it is possible to reduce the level of detail developed for each design phase. That is, if the design will not be "handed-off" to a totally separate construction entity, then there is less chance for error when implementing less detailed designs. Indeed, since much of the site understanding develops during implementation of remediation systems, it is desirable to have less detailed, more flexible designs that can quickly and easily accommodate new information. For example, it is often the case that during well installation, new "pockets" of contamination are discovered that will require additional treatment wells to be installed. These additional wells in turn may cause a substantial increase in the total extracted vapor flow. If the aboveground system components are not readily modified to accommodate the increased flow, then there will be significant time and cost implications for changing the detailed design. Using the design/build model, the project manager can make much more timely and less costly course corrections to react to these changes in project scope.

(3) As shown in Figure 11-1, a progressive, design/build approach would involve an initial phase of remediation or a pilot test to further the understanding of the site and the applicability of soil venting to remediate the site. Data collected from RI activities provide the basis of the "best guess" design parameters necessary to implement a pilot or small-scale venting system. The pilot or initial phase of remediation would be ongoing while additional phases of remediation are designed. In addition to improving the conceptual model, this test provides critical design data for future system installation. The largest size that is advisable for an initial soil venting phase is specific to the site and the cost/benefit analysis that aids in evaluating remedial options. The designer/practitioner must weigh the cost of multiple mobilizations against the cost of implementing the venting system for the time necessary to gain further insight about venting applicability. (At sites with deep contaminated unsaturated zones, each SVE well and associated monitoring wells/points may cost as much as the entire drilling program at a site with shallow contamination.) In some cases, the remediation equipment can be moved around a larger contaminated site to address the site sequentially essentially in pieces. This approach requires more time, but would have a lower capital cost for equipment. If operational costs are low and there is no need to complete the remediation in a short time, this may be cost effective.



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Figure 11-1. Phased Remediation Process Flow Chart

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(4) It is conceivable that a venting system of up to 5 wells can be installed and operated based on the limited data available from a RI. For some sites with limited areal contaminant extent, the well network employed for the initial phase of venting remediation may be sufficient for the "full-scale" remediation. At such sites, the design team should develop:

- A preliminary site plan showing the location of the first round of SVE/BV wells with associated monitoring points. These monitoring points are crucial for verifying flow and vacuum design assumptions for future phases.
- Well construction and surface cover details (plans & specifications).
- A detailed P&I diagram for the construction of the aboveground components with concise specification of major system components.
- A preliminary set of electrical plans (single line diagram and control schemata) referencing relevant electrical and NFPA codes.

These plans should be sufficient for developing accurate cost estimates and for gathering price quotes for high-cost components. Other plans and documents can be developed as implementation progresses, as long as the designer remains integral to the process.

*c. Rental vs. Purchase of Equipment.* It may be prudent, to rent and/or install temporary aboveground equipment to minimize costs as the appropriateness of the venting design is verified and the long-term concentration trends are known. A phased-approach, as described above, is particularly suited for this. The offgas treatment system is often best rented unless significant data exist to project contaminant concentrations appropriate for the technology over a long period of time. By renting the treatment units, flexibility in adjusting to the changing offgas concentrations is available. This is especially important if the duration is expected to be short. The re-use of purchased equipment at other sites is often hampered by logistical or financial (i.e., funding sources) issues. A financial analysis of the costs of purchasing vs. rental should be conducted, considering the customer's desires for equipment ownership at the completion of the project.

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**Appendix A  
References**

**A-1. Required Publications**

Code of Federal Regulations

**29 CFR 1910/29**

**29 CFR 1910.120 (b)**

**29 CFR 1926.65 (b)**

**40 CFR, Part 60**

**40 CFR 264**

Department of the Army

<http://www.usace.army.mil/inet/usace-docs/>

**EP 415-1-261**

Quality Assurance Representative's Guide

**ER 385-1-92**

Safety and Occupational Health Document Requirements for HTRW Activities

**ER 1110-1-263**

Chemical Data Quality Management for Hazardous Waste Remedial Activities (Appendix D)

**ER 1110-1-1300**

Cost Engineering Policy and General Requirements

**ER 1110-2-1150**

Engineering and Design for Civil Works Projects

**ER 1110-3-1301**

Cost Engineering Policy and General Requirements for Hazardous, Toxic, and Radioactive Waste (HTRW), Remedial Action Cost Estimates

**ER 1110-345-100**

Design Policy for Military Construction

**ER 1110-345-700**

Design Analysis

**ER 1165-2-132**

Hazardous, Toxic, and Radioactive Waste (HTRW) Guidance for Civil Works Projects

**ER 1180-1-6**

Construction Quality Management

**EM 200-1-2**

Technical Project Planning

**EM 200-1-3**

Requirements for the Preparation of Sampling and Analysis Plans

**EM 385-1-1**

Safety and Health Requirements

**EM 1110-1-4005**

In Situ Air Sparging: Engineering and Design

**EM 1110-1-4007**

Safety and Health Aspects of HTRW Remediation Technologies

**EM 1110-1-4010**

Multi-Phase Extraction: Engineering and Design.

**CE-15995**

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**EM 1110-1-4001**

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**USEPA 1991c**

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U.S. EPA. 1995ba. *Remedial Design/Remedial Action Handbook*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response. EPA 540/R-95//059, OSWER 9355.0-04B, PB95-963307. Available from NTIS, Superfund Docket. 317 pp.

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**A58.1**

Minimum Design Loads for Buildings and Other Structures

**B31.1**

Power Piping

**B31-3**

**C80.1**

Rigid Steel Conduit, Zinc Coated

**C80.5**

Rigid Aluminum Conduit

**ISA-S5.1**

Instrumentation Symbols and Identification

**MSS SP-58,-69,-89,-90**

American Petroleum Institute (API)

**API-650**

Field Erected Tanks

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**RP500A**

Recommended Practice for Classification of Areas for Electrical Installations in Petroleum Refineries

**RP500B**

Recommended Practice for Classification of Areas for Electrical Installation at Drilling Rigs and Production Facilities on Land and on Fixed Marine Platforms

**RP500C**

Electrical Installation at Petroleum and Gas Pipeline Transportation Facilities

American Society for Testing and Materials (ASTM)

**C150**

Specifications for Portland Cement

**D422**

Methods for Particle-Size Analysis of Soils

**D698**

Test Method for Laboratory Compaction Characteristics of Soils Using Standard Effort

**D1586**

Standard Method for Penetration Test and Split-Barrel Sampling of Soils

**D1587**

Thin-Walled Tube Sampling of Soils

**D1785**

Specifications for Poly (Vinyl Chloride) (PVC) Plastic Pipe, Schedules 40, 80, and 120

**D2216**

Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock

**D2241**

Specifications for Poly (Vinyl Chloride) (PVC) Pressure-Rated Pipe (SDR-Series)

**D2321**

Standard Practice for Underground Installation of Flexible Thermoplastic Sewer Pipe

**D2325**

Test Method for Capillary-Moisture Relationships for Coarse- and Medium-Textured Soils by Porous-Plate Apparatus

**D2487**

Classification of Soils for Engineering Purposes

**D2488**

Practice for Description and Identification of Soils (Visual-Manual Procedure)

**D2850**

Test Method for Unconsolidated, Undrained Strength of Cohesive Soils in Triaxial Compression

**D3350**

Standard Specifications for Polyethylene Plastics Pipe and Fittings Materials

**D3416**

Standard Test Method for Total Hydrocarbons, Methane, and Carbon Monoxide in the Atmosphere (Gas Chromatographic Method)

**D5092**

Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers

**D5126**

Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in the Vadose Zone

**D5314**

Standard Guide for Soil Gas Monitoring in the Vadose Zone

**F480**

Thermoplastic Well Casing Pipe/Couplings Made in Standard Dimension Ratios (SDR) Schedule 40/80, specifications

American Water Works Association (AWWA)

**A100**

Water Wells

SAPC

**E245**

**E245a**

**E418**

**E1243**

**A-6**

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**Z501 Design Guide**

Institute of Electrical and Electronics Engineers (IEEE)

**C.2**

National Electrical Safety Code

**141**

Recommended Practices for Electrical Power Distribution for Industrial Plants

**518**

The Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

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

National Sanitary Foundation (NSF)

**Standard 14**

Plastics, Piping Components and Related Materials

Underwriters Laboratory (UL)

**UL-58**

Underground Tanks

**UL-80**

Oil Burner Fuel Tanks

**UL-142**

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## Appendix B Properties of Common Organic Pollutants

### B-1. Introduction

Appendix B 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 SVE/BV. In addition, this information may be needed in calculating various operating parameters or outcomes of an SVE/BV system at a given site with a given suite of contaminants of concern.

### B-2. List of Tables

- B-1: Selected Compounds and Their Chemical Properties. Lists molecular weight, compound boiling point, vapor pressure, and equilibrium vapor concentration.
- B-2: Physicochemical Properties of PCE and Associated Compounds. Lists molecular weight, liquid density, melting point, boiling point, vapor pressure, water solubility, log octanol-water coefficient, soil sorption coefficient, and Henry's Law constant for PCE; TCE; 1,1-DCE; 1,2-DCE; and vinyl chloride.
- B-3: Physicochemical Properties of TCA and Associated Compounds. Lists same properties as Table B-2 for 1,1,1-TCA; 1,1-DCA; and CA.
- B-4: Physical Properties of Fuel Components. Lists molecular weight, solubility, soil sorption coefficient, log octanol-water coefficient, and vapor pressure for n-alkanes, isoalkanes, cycloalkanes, alkenes, aromatics, and PAHs.
- B-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.
- B-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.
- B-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 automotive diesel oil and distillate marine diesel fuel.
- B-8: Henry's Law Constants for Selected Organic Compounds. Lists values of H at 20-25 C for chlorinated nonaromatics, chlorinated ethers, monocyclic aromatics, pesticides, PCBs, and polycyclic aromatics.

- B-9: Chemical and Physical Properties of TPH Components. Lists molecular weight, water solubility, specific gravity, vapor pressure, Henry's Law constant, diffusivity,  $K_{oc}$ , log  $K_{ow}$ , Fish Bioconcentration Factor (BCF), and Surface-Water  $T_{1/2}$ , for alcohols, cycloalkanes, cycloalkenes, chlorinated aliphatics, ethers, ketones, methyl alkanes, methyl alkenes, mono- and polycyclic aromatic hydrocarbons, simple alkanes, and simple alkenes.
- B-10: Dimensionless Henry's Law Constants for Typical Organic Compounds. Lists values of H for various compounds at different temperatures.
- B-11: Chemical Properties of Hydrocarbon Constituents. Lists liquid density, Henry's Law Constant, water solubility, vapor pressure, vapor density, and  $K_{oc}$  for n-alkanes, mono-aromatics, phenols, and di-aromatics.
- B-12: Composition of a Regular Gasoline. Lists chemical formula, molecular weight, mass fraction, and mole fraction of 58 components of regular gasoline.
- B-13: Composition of a Weathered Gasoline. Lists same properties as Table B-12 for 58 components of weathered gasoline.

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**Table B-1**  
**Selected Compounds and Their Chemical Properties**

| Compound               | M <sub>w</sub><br>(g/mole) | T <sub>b</sub> (1 atm)<br>(K) | P <sub>v</sub> <sup>o</sup> (K)<br>(atm) | C <sub>est</sub><br>(mg/l) |
|------------------------|----------------------------|-------------------------------|--|----------------------------|
| n-Pentane              | 72.2                       | 309                           | 0.57                                     | 1700                       |
| 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                        | dec. @473K                    | 0.0002                                   | 2.6                        |

Note:

M<sub>w</sub> - molecular weight.

T<sub>b</sub>(1 atm) - compound boiling point at 1 atm absolute pressure.

P<sub>v</sub><sup>o</sup> (293 K), - vapor pressure measured at 293 K.

C<sub>est</sub> - equilibrium vapor concentration.

dec. - decomposes

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**Table B-2**  
**Physiochemical Properties of PCE and Associated Compounds\***

| Formula   | PCE<br>C <sub>2</sub> Cl <sub>4</sub> | TCE<br>C <sub>2</sub> HCl <sub>3</sub> | 1,1-DCE<br>C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub> | t-1,2-DCE<br>C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub> | c-1,2-DCE<br>C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub> | V C<br>C <sub>2</sub> H <sub>3</sub> Cl |
|---|---------------------------------------|--|--|--|--|---|
| Molecular weight (g/mol)                            | 165.85                                | 131.40                                 | 96.95  | 96.95  | 96.95  | 62.5                                    |
| Liquid density (g/cm <sup>3</sup> )                 | 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 <sup>1</sup>                        | 500  | 5.3  | 2.7  | 2300                                    |
| Water solubility (mg/l)                             | 150                                   | 1100 <sup>1</sup>                      | 400  | 6300   | 3500   | 1100                                    |
| Log octanol - water coefficient (K <sub>ow</sub> )  | 3.14                                  | 2.42                                   | 2.13   | 2.09   | 1.86   | 1.23                                    |
| Soil sorption coefficient (K <sub>oc</sub> ) (l/kg) | 665                                   | 160 <sup>2</sup>                       | 65   | 59   | 35   | 8.2                                     |
| Henry's Law constant (atm. m <sup>3</sup> /mol)     | 0.023                                 | .0103 <sup>1</sup>                     | 0.154  | 0.0066 <sup>1</sup>  | 0.0075 <sup>1</sup>  | 0.695                                   |

Arthur D. Little, Inc. (1987). *The installation restoration program toxicology guide, Volume 1*. Section 2:1-16.

All values are at 293 K, unless otherwise indicated.

#Value is a specific gravity measurement.

<sup>1</sup>At 298 K.

<sup>2</sup>From Lyman et al.(1982) Handbook of Chemical Property Estimation Methods

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**Table B-3**  
**Physiochemical Properties of TCA and Associated Compounds\***

| Formula   | 1,1,1-TCA<br>C <sub>2</sub> H <sub>3</sub> Cl <sub>3</sub> | 1,1-DCA<br>C <sub>2</sub> H <sub>4</sub> Cl <sub>2</sub> | CA<br>C <sub>2</sub> H <sub>5</sub> Cl |
|---|--|--|--|
| Molecular weight (g/mol)                            | 133.42   | 98.97  | 64.52                                  |
| Liquid density (kg/m <sup>3</sup> )                 | 1.325  | 1.175  | 0.921 <sup>1</sup>                     |
| Melting point (K)                                   | 240  | 176.3  | 132.15                                 |
| Boiling point (K)                                   | 347  | 330.3  | 285.5                                  |
| Vapor pressure (mmHg)                               | 100  | 182  | 1000                                   |
| Water solubility (mg/l)                             | 950  | 5500   | 5700                                   |
| Log octanol - water coefficient (K <sub>ow</sub> )  | 2.49   | 1.79   | 1.43                                   |
| Soil sorption coefficient (K <sub>oc</sub> ) (l/kg) | 152  | 30   | 14.9                                   |
| Henry's Law constant (atm. m <sup>3</sup> /mol)     | 0.0276 <sup>2</sup>  | 0.0057 <sup>2</sup>                                      | 0.011                                  |

\*All values are at 293 K, unless otherwise indicated.

<sup>1</sup>At 273 K

<sup>2</sup>At 298 K

Arthur D. Little, Inc. (1987). *The installation restoration program toxicology guide, Volume 1. Section 2:1-16.*

**Table B-4**  
**Physical Properties of Fuel Components**

| Component                     | MW     | Solubility | Koc     | Log Kow | VP        | References |
|-------------------------------|--------|------------|---------|---------|-----------|------------|
| <u>n-Alkanes</u>              |        |            |         |         |           |            |
| n-Butane                      | 58.12  | 61         |         |         | 1555.33   | IIIIA      |
| n-Decane                      | 142.28 | 0.009 (20) |         |         | 2.7       | IB/IIIB    |
| n-Dodecane                    | 170.33 | 0.0037     | 5500000 | 7.06    | 0.3       | IA/C/C/A   |
| n-Hexane                      | 86.18  | 9.5        | 3830    | 3.9     | 121.24    | ID/C/C/A   |
| n-Heptane                     | 100.20 | 2.4 (20)   |         |         | 35.55     | IB/IIIA    |
| n-Nonane                      | 128.25 | 0.07 (20)  |         |         | 3.22      | IB/IIIB    |
| n-Octane                      | 114.23 | 0.0657     | 73000   | 4.00    | 10.46     | IE/C/E/A   |
| n-Pentane                     | 72.15  | 38.5       |         |         | 424.38    | ID/IIIA    |
| n-Tridecane                   | 184.35 | 0.013      |         |         |           | IB/II      |
| n-Undecane                    | 156.31 |            |         |         | 1 (32.7)  | IIIB       |
| <u>Isoalkanes</u>             |        |            |         |         |           |            |
| 2-Methyldecane                | 156.31 |            |         |         |           | IIII       |
| 2-Methylhexane                | 100.20 |            |         |         | 51.9      | IIIIA      |
| 2-Methylpentane               | 86.18  | 13.8       |         |         | 171.5     | ID/IIIA    |
| 2,4-Dimethylhexane            | 114.23 |            |         |         | 23.32     | IIIIA      |
| 2,5-Dimethylhexane            | 114.23 |            |         |         |           | IIII       |
| 2,2,3-Trimethylpentane        | 114.23 |            | 36000   | 4.87    |           | IIC/C/I    |
| 2,2,4-Trimethylpentane        | 114.23 | 0.56       | 36000   | 5.02    |           | IB/C/E     |
| 3-Methylhexane                | 100.20 |            |         |         |           | IIII       |
| 3-Methylpentane               | 86.18  |            | 3830    | 3.9     |           | IIC/C/I    |
| 3,4-Dimethyloctane            | 142.28 |            |         |         |           | IIII       |
| 4-Methylheptane               | 114.23 |            |         |         |           | IIII       |
| Isobutane                     | 58.12  | 48.9       |         |         | 2252.75   | ID/IIIA    |
| Isododecane                   | 170.33 |            |         |         |           | IIII       |
| Isopentane                    | 72.15  | 47.7       | 900     | 2.3     | 574.89    | IE/C/E/A   |
| Isoundecane                   | 156.31 |            |         |         |           | IIII       |
| <u>Cycloalkanes</u>           |        |            |         |         |           |            |
| 1,3,5-Trimethylcyclohexane    | 126.24 |            | 50500   | 5.02    |           | IIC/C/I    |
| Cyclohexane                   | 84.16  | 55.6       | 1330    | 3.44    | 77.55     | IE/C/E/A   |
| Methylcyclohexane             | 98.19  | 14 (20)    | 6070    | 4.1     | 144       | IIC/C/B    |
| Methylcyclopentane            | 83.15  | 42.7       | 1400    | 2.35    |           | IE/C/E     |
| <u>Alkenes</u> trans-2-Butene | 56.11  |            |         |         | 760 (0.9) | IIIB       |
| 2-Methyl-2-butene             | 70.13  |            |         |         |           | IIII       |

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**Table B-4**  
**(Concluded)**

| Component                  | MW     | Solubility | Koc    | Log Kow | VP           | References |
|----------------------------|--------|------------|--------|---------|--------------|------------|
| <u>Aromatics</u>           | 120.19 |            |        |         |              | ////       |
| 1-Methyl-3-ethylbenzene    |        |            |        |         |              | ////       |
| 1-Methyl-3-n-propylbenzene | 134.22 |            |        |         |              | ////       |
| 1,2,3-Trimethylbenzene     | 120.19 |            | 2150   | 4.65    |              | //C/C/     |
| 1,2,4-Trimethylbenzene     | 120.19 | 57.6       | 2150   | 3.65    |              | /E/C/C/    |
| 1,3,5-Trimethylbenzene     | 120.19 |            | 2150   | 3.65    | 1.73         | //C/C/A    |
| 1,2,3,4-Tetramethylbenzene | 134.22 |            |        |         |              | ////       |
| Benzene                    | 78.11  | 1760       | 65     | 2.13    | 75.2         | /E/C/C/A   |
| Ethylbenzene               | 106.17 | 152        | 1200   | 3.34    | 7.08         | /D/F/F/A   |
| Isopropylbenzene           | 120.19 | 50.1       |        | 3.43    |              | /E//E/     |
| Toluene                    | 92.14  | 515        | 240    | 2.69    | 21.84        | /E/C/C/A   |
| Xylenes                    | 106.17 | 175        | 700    | 3.16    | 6/16         | /E/C/C/A   |
| <u>PAHs</u>                | 142.20 | 27         | 3570   | 3.87    |              | B/B/C/C/   |
| 1-Methylnaphthalene        |        |            |        |         |              |            |
| 2-Methylnaphthalene        | 142.20 |            | 3570   | 3.87    |              | B//C/C/    |
| Acenaphthene               | 154.21 | 4.09       | 5250   | 3.98    | 0.0016 (25)  | B/E/F/F/F  |
| Acenaphthylene             | 152.20 | 3.93       | 2890   | 3.72    | 0.03         | B/B/F/F/F  |
| Anthracene                 | 178.23 | 1.29       | 13500  | 4.45    | 0.00024 (25) | B/B/C/E/F  |
| Chrysene                   | 228.20 | 0.006      | 220000 | 5.61    | 6.3E-09 (25) | B/B/F/F/F  |
| Naphthalene                | 128.16 | 31.7       | 962    | 3.3     | 0.09 (25)    | B/E/C/C/F  |
| Phenanthrene               | 178.22 | 1.24       | 16000  | 4.45    | 9.4E-04 (25) | B/E/F/F/F  |
| Pyrene                     | 202.24 | 0.15       | 44000  | 4.88    | 2.5E-06 (25) | B/E//E/F   |

Note:

References

MW/Solubility/Koc/Log Kow/VP

A. EPA, 1989d.

B. Verschuere (1983).

C. IRP (1987).

D. Guard et al. (1983).

E. Lyman, Rechl, and Rosenblatt (1982).

F. A. D. Little (1981).

Solubility in mg/L water at 198 K, unless otherwise noted in parentheses.

Vapor Pressure (VP) of pure compound in mmHg 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 B-5**  
**Selected Specification Properties of Aviation Gas Turbine Fuels<sup>a</sup>**

| Characteristic                                     | Civil ASTM D 1655 |                 | Military <sup>b</sup> |                   |                                 |                    |
|--|-------------------|-----------------|-----------------------|-------------------|---------------------------------|--------------------|
|  |                   |                 | 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 <sup>c</sup> kerosene USAF | JP-8 Kerosene USAF |
| Composition  |                   |                 |                       |                   |                                 |                    |
| aromatics, vol. % max                              | 20 <sup>d</sup>   | 20 <sup>d</sup> | 25                    | 25                | 5                               | 25                 |
| sulfur, wt % max                                   | 0.3               | 0.3             | 0.4                   | 0.4               | 0.1                             | 0.4                |
| Volatility   |                   |                 |                       |                   |                                 |                    |
| distillation-10% received temperature-50% received | 204               | 188             | 190                   | 205               | 196                             | 205                |
| max k-endpoint                                     | 573               |                 | 543                   | 563               | 561                             | 573                |
| vapor pressure at 311 K kPa max (psi)              |                   | 21(3)           | 14-21(2-3)            |                   |                                 |                    |
| density at 288 K, kg/m <sup>3</sup>                | 775-840           | 751-802         | 751-802               | 788-845           | 779-806                         | 775-840            |
| Fluidity   |                   |                 |                       |                   |                                 |                    |
| freezing-point, k max                              | 233 <sup>e</sup>  | 223             | 215                   | 227               | 230                             | 223                |
| viscosity at 253 K, mm <sup>3</sup> /s max (=cSt)  | 8.0               |                 |                       | 8.5               | 8.0                             | 8.0                |
| Combustion   |                   |                 |                       |                   |                                 |                    |
| heat content, MJ/kg, min                           | 42.8              | 42.8            | 42.8                  | 42.6              | 43.5                            | 42.8               |
| smoke point, mm, min                               | 20 <sup>f</sup>   | 20 <sup>f</sup> | 20                    | 19                | 35 <sup>c</sup>                 | 20                 |
| H <sub>2</sub> content, wt % min                   |                   |                 | 13.6                  | 13.5              | 14.2 <sup>c</sup>               | 13.6               |

Note:

<sup>a</sup>From Dukek (1978); full specification requires other tests.

<sup>b</sup>USAF, US Air Force; USN, US Navy

<sup>c</sup>Estimated properties for advanced supersonic fuel

<sup>d</sup>Fuel up to 25 vol % aromatics may be supplied on notification (22 vol % for Jet A-1, Jet B).

<sup>e</sup>International airlines use Jet A-1 with 223 k freeze-point.

<sup>f</sup>Fuel with 18 smoke point may be supplied on notification (19 for Jet A-1, Jet B).

max = maximum

min = minimum

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.

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**Table B-6**  
**Detectable Hydrocarbons Found in U.S. Finished Gasolines at a Concentration of 1% or More<sup>a</sup>**

| Chemical   | Weight %        |                               |
|--|-----------------|-------------------------------|
|  | Estimated Range | Weighted Average <sup>b</sup> |
| Toluene  | 5-22            | 10                            |
| 2-Methylpentane<br>+ 4-Methyl-cis-2-pentene<br>+ 3-Methyl-cis-2-pentene <sup>c</sup> | 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<br>+ 1-cis-2-Dimethylcyclopentane<br>+ 3-Methylhexane <sup>c</sup> | <1-5            | 1                             |
| Benzene  | <1-4            | 2                             |
| 2,2,3-Trimethylpentane   | <1-4            | 2                             |
| Methyl tertiary butyl ether (MTBE)   | <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                             |

<sup>a</sup>Provided by American Petroleum Institute

<sup>b</sup>The sum of the weighted average does not equal 100% because numerous components were detected at less than 1%.

<sup>c</sup>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.

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**Table B-7****Major Component Streams of European Automotive Diesel Oil (Diesel Fuel No. 2) and Distillate Marine Diesel Fuel (Diesel Fuel No. 4)<sup>a</sup>**

| <b>Toxic Substances Control Act (TSCA) Inventory Name and Identification Number<sup>b</sup></b> | <b>Refinery Process Stream (nomenclature used in Europe)</b> | <b>Automotive Diesel Oil (vol. %)</b> | <b>Distillate Marine Diesel Fuel (vol. %)</b> |
|---|--|---------------------------------------|---|
| Straight-run middle distillate [6]<br>Straight-run gas oil [7]                                  | Straight-run (atmospheric) gas oil<br>- light<br>- heavy     | 40-100<br>0-3                         | 40-100<br>0-50                                |
| Light vacuum distillate [19]  | Vacuum gas oil   | 0-10                                  | 0-20  |
| Light thermally cracked distillate [30]   | Thermally cracked gas oil                                    | 0-20                                  | 0-30  |
| Light catalytically cracked distillate [24]   | Light catalytically cracked gas oil (cycle oil)              | 0-25                                  | 0-40  |

<sup>a</sup>From CONCAWE (1985).<sup>b</sup>The numbers in brackets correlate with these products in Figure 1 and Table 2 in the monograph Occupational Exposures in Petroleum Refining, contained in the reference cited below.

World Health Organization, International Agency for Research on Cancer. (1989). "ARC 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.

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**Table B-8**  
Henry's Law Constants (H, atm-m<sup>3</sup>/mol) for Selected Organic Compounds [Data Obtained from Mabey et al. (1982) and Mackay and Shiu (1981)]

| Compound                        | H       | t (K) <sup>a</sup> | Compound   | H        | t (K) <sup>a</sup> |
|---------------------------------|---------|--------------------|--|----------|--------------------|
| <b>Chlorinated Nonaromatics</b> |         |                    | <b>Monocyclic and Polycyclic Aromatics</b>       |          |                    |
| Benzene                         | 0.0055  | 298                | Naphthalene                                      | 0.00046  | 298                |
| Chlorobenzene                   | 0.0036  | 293/298            | Acenaphthene                                     | 0.000091 | 298                |
| o-Dichlorobenzene               | 0.0019  | 293                | Acenaphthylene                                   | 0.0015   | 293/298            |
| m-Dichlorobenzene               | 0.0036  | 298                | Anthracene                                       | 0.000086 | 298                |
| p-Dichlorobenzene               | 0.0031  | 298                | Phenanthrene                                     | 0.00023  | 298                |
| 1,2,4-Trichlorobenzene          | 0.0023  | 298                |  |          |                    |
| Methyl chloride                 | 0.04    | 293                | Hexachlorobenzene                                | 0.00068  | 293/298            |
| Methyl bromide                  | 0.20    | 293                | Toluene  | 0.0067   | 293                |
| Methylene chloride              | 0.0020  | 293/298            | Ethylbenzene                                     | 0.0066   | 293                |
| Chloroform                      | 0.0029  | 293                | o-Xylene   | 0.0050   | 298                |
| Bromodichloromethane            | 0.0024  | 293/295            | m-Xylene   | 0.0070   | 298                |
| Dibromochloromethane            | 0.00099 | 293/295            | p-Xylene   | 0.0071   | 298                |
| Bromoform                       | 0.00056 | 293                | 1,2,3-Trimethylbenzene                           | 0.0032   | 298                |
| Dichlorodifluoromethane         | 3.0     | 298                | 1,2,4-Trimethylbenzene                           | 0.0059   | 298                |
| Trichlorofluoromethane          | 0.11    | 293                | 1,3,5-Trimethylbenzene                           | 0.0060   | 298                |
| Carbon tetrachloride            | 0.023   | 293                | Propylbenzene                                    | 0.0070   | 298                |
| Chloroethane                    | 0.15    | 293                | Isopropylbenzene                                 | 0.0013   | 298                |
| 1,1-Dichloroethane              | 0.0043  | 293                | 1-Ethyl-2-methylbenzene                          | 0.0043   | 298                |
| 1,2-Dichloroethane              | 0.00091 | 293                | 1-Ethyl-4-methylbenzene                          | 0.0050   | 298                |
| 1,1,1-Trichloroethane           | 0.03    | 298                | n-Butylbenzene                                   | 0.013    | 298                |
| 1,1,2-Trichloroethane           | 0.00074 | 293                | Isobutylbenzene                                  | 0.033    | 298                |
| 1,1,2,2-Tetrachloroethane       | 0.00038 | 293                | sec-Butylbenzene                                 | 0.014    | 298                |
| Hexachloroethane                | 0.0025  | 293/295            | tert-Butylbenzene                                | 0.012    | 298                |
| Vinyl chloride                  | 0.081   | 298                | 1,2,4,5-Tetramethylbenzene                       | 0.025    | 298                |
| 1,1-Dichloroethene              | 0.19    | 298/293            | 1-Isopropyl-4-methylbenzene                      | 0.0080   | 298                |
| 1,2-trans-Dichloroethene        | 0.067   | 293                | n-Pentylbenzene                                  | 0.0060   | 298                |
| Trichloroethene                 | 0.0091  | 293                | <b>Pesticide and Related Compounds, and PCBs</b> |          |                    |
| Tetrachloroethene               | 0.0153  | 293                | Ethylene dibromide (EDB) <sup>b</sup>            | 0.00082  | 298                |
| 1,2-Dichloropropane             | 0.0023  | 293                | trans-Chlordane                                  | 0.000094 | 298                |

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**Table B-8**  
**(Concluded)**

|                             |         |         |                           |         |     |
|-----------------------------|---------|---------|---------------------------|---------|-----|
| trans-1,3-Dichloropropene   | 0.0013  | 293/298 | Heptachlor                | 0.0040  | 298 |
| Hexachlorocyclopentadiene   | 0.016   | 298     | Heptachlor epoxide        | 0.00039 | 298 |
| Hexachlorobutadiene         | 0.026   | 293     | 2,3,7,8-TCDD              | 0.0021  | —   |
| <b>Chlorinated Ethers</b>   |         |         | Aroclor 1016 <sup>c</sup> | 0.00033 | 298 |
| Bis(chloromethyl)ether      | 0.00021 | 293/298 | Aroclor 1221 <sup>c</sup> | 0.00017 | 298 |
| Bis(2-chloroisopropyl)ether | 0.00011 | 293     | Aroclor 1242 <sup>c</sup> | 0.0020  | 298 |
| 4-Chlorophenylphenylether   | 0.00022 | 293     | Aroclor 1248 <sup>c</sup> | 0.0036  | 298 |
| 4-Bromophenylphenylether    | 0.00010 | 293/298 | Aroclor 1254 <sup>c</sup> | 0.0026  | —   |

<sup>a</sup>Where two temperatures are given, the first is the temperature at which the vapor pressure was measured, and the second is the temperature at which the solubility was measured.

<sup>b</sup>Vapor pressure data from Stull (1947), and solubility data from Stephen and Stephen (1963).

<sup>c</sup>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.

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Table B-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 <sup>3</sup> /mol 298 K | Diffusivity cm <sup>2</sup> /sec | K <sub>oc</sub> mL/g | Log K <sub>ow</sub> | Fish BCF L/kg | Surface-Water T <sub>1/2</sub> (days) |      |
|-------------------------------|------------------|-----------------------------|------------------|----------------------------|--|----------------------------------|----------------------|---------------------|---------------|---------------------------------------|------|
|                               |                  |                             |                  |                            |  |                                  |                      |                     |               | Low                                   | High |
| <b>Alcohols</b>               |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| 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                |               |                                       |      |
| <b>Cycloalkanes</b>           |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| Cyclopentane                  | 70.14            | 160                         | 0.751            | 42.4                       | 1.9E+01  |                                  |                      |                     |               |                                       |      |
| Methyl cyclohexane            | 98.19            | 14                          | 0.77             | 6.18                       | 4.3E+01  |                                  |                      |                     |               |                                       |      |
| <b>Cycloalkenes</b>           |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| Cyclohexene                   | 84.16            | 55 (20°C)                   | 0.779            |                            |  |                                  |                      |                     |               |                                       |      |
| Cyclopentene                  | 68.12            |                             | 0.77             | 77 (20°C)                  |  |                                  |                      |                     |               |                                       |      |
| <b>Chlorinated Aliphatics</b> |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| 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                |               |                                       |      |
| <b>Ether</b>                  |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| Methyl-t-butyl ether (MTBE)   | 88               | 4,800                       | 0.74             | 250                        | 5.9E-03  | 0.10172                          | 41                   | 1.2                 | 1.5           | 28-180                                |      |
| <b>Ketones</b>                |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| Methyl isobutyl ketone        | 100.2            | 20,400                      | 0.8017           | 14.5                       | 9.4E-05  | 0.07588                          | 19 to 106            | 1.19                |               |                                       |      |
| <b>Methyl Alkanes</b>         |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |      |
| 2,3-Dimethylbutane            | 86.7             | 19.1                        |                  | 31.3                       | 1.3E+02  |                                  |                      |                     |               |                                       |      |
| 2,3-Dimethylpentane           | 100.21           | 5.25                        |                  | 9.18                       | 1.8E+02  |                                  |                      |                     |               |                                       |      |

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**Table B-9**  
(Continued)

| Constituents           | Molecular Weight | Water Solubility mg/L 298 K | Specific Gravity | Vapor Pressure mm Hg 298 K | Henry's Law Constant atm-m <sup>3</sup> /mol 298 K | Diffusivity cm <sup>2</sup> /sec | K <sub>oc</sub> mL/g | Log K <sub>ow</sub> | Fish BCF L/kg | Surface-Water T <sub>1/2</sub> (days) |
|------------------------|------------------|-----------------------------|------------------|----------------------------|--|----------------------------------|----------------------|---------------------|---------------|---------------------------------------|
|                        |                  |                             |                  |                            |  |                                  |                      |                     |               | Low -High                             |
| 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  |                                  |                      |                     |               |                                       |
| <b>Methyl Alkenes</b>  |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |
| 2-Methyl-1-butene      | 70.14            |                             | 0.65             |                            |  |                                  |                      |                     |               |                                       |
| 2-Methyl-2-butene      | 70.14            |                             | 0.668            |                            |  |                                  |                      |                     |               |                                       |

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Table B-9  
(Continued)

| Constituents                            | Molecular Weight | Water Solubility mg/L 298 K | Specific Gravity | Vapor Pressure mm Hg 298 K | Henry's Law Constant atm-m <sup>3</sup> /mol 298 K | Diffusivity cm <sup>2</sup> /sec | K <sub>OC</sub> mL/g | Log K <sub>OW</sub> | Fish BCF L/kg | Surface-Water T <sub>1/2</sub> (days) |
|---|------------------|-----------------------------|------------------|----------------------------|--|----------------------------------|----------------------|---------------------|---------------|---------------------------------------|
|   |                  |                             |                  |                            |  |                                  |                      |                     |               | Low -High                             |
| 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            |                             |                  |                            |  |                                  |                      |                     |               |                                       |
| <b>Monocyclic Aromatic Hydrocarbons</b> |                  |                             |                  |                            |  |                                  |                      |                     |               |                                       |
| Benzene                                 | 78               | 1.780                       | 0.88             | 95                         | 5.5E-03  | 9.30E-02                         | 49 to 100            | 1.56 to 2.15        | 5.2           | 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             | 9.5                        | 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                |                     |               |                                       |

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**Table B-9**  
**(Continued)**

| Constituents                     | Molecular Weight | Water Solubility mg/L 298 K | Specific Gravity | Vapor Pressure mm Hg 298 K | Henry's Law Constant atm-m <sup>3</sup> /mol 298 K | Diffusivity cm <sup>2</sup> /sec | K <sub>oc</sub> mL/g | Log K <sub>ow</sub> | Fish BCF L/kg | Surface-Water T <sub>1/2</sub> (days) |
|----------------------------------|------------------|-----------------------------|------------------|----------------------------|--|----------------------------------|----------------------|---------------------|---------------|---------------------------------------|
|                                  |                  |                             |                  |                            |  |                                  |                      |                     |               | Low -High                             |
| 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                                  |
| 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  |                                  |                      |                     |               |                                       |

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Table B-9  
(Continued)

| Constituents    | Molecular Weight | Water Solubility mg/L 298 K | Specific Gravity | Vapor Pressure mm Hg 298 K | Henry's Law Constant atm-m <sup>3</sup> /mol 298 K | Diffusivity cm <sup>2</sup> /sec | K <sub>oc</sub> mL/g | Log K <sub>ow</sub> | Fish BCF L/kg | Surface-Water T <sub>1/2</sub> (days) |
|-----------------|------------------|-----------------------------|------------------|----------------------------|--|----------------------------------|----------------------|---------------------|---------------|---------------------------------------|
|                 |                  |                             |                  |                            |  |                                  |                      |                     |               | Low -High                             |
| 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           |                             |                  |                            |  |                                  |                      |                     |               |                                       |
| 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               |                             |                  |                            |  |                                  |                      |                     |               |                                       |

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Table B-9

(Continued)

| Constituents    | Molecular Weight | Water Solubility<br>mg/L 298 K | Specific Gravity | Vapor Pressure<br>mm Hg 298 K | Henry's Law<br>Constant atm-<br>m <sup>3</sup> /mol 298 K | Diffusivity<br>cm <sup>2</sup> /sec | K <sub>OC</sub><br>mL/g | Log<br>K <sub>OW</sub> | Fish<br>BCF<br>L/kg | Surface-Water<br>T <sub>1/2</sub> (days) |
|-----------------|------------------|--------------------------------|------------------|-------------------------------|---|-------------------------------------|-------------------------|------------------------|---------------------|--|
|                 |                  |                                |                  |                               |   |                                     |                         |                        |                     | Low -High                                |
| 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            |                                |                  |                               |   |                                     |                         |                        |                     |  |

Note:

BCF - Bioconcentration factor

T<sub>1/2</sub> - half life

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 B-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  |

**Table B-10**  
**(Concluded)**

| Component                      | 283 K   | 289 K   | 293 K    | 298 K    | 303 K    |
|--------------------------------|---------|---------|----------|----------|----------|
| 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: USEPA (1991d). (Adapted from Howe, Mullins, and Rogers (1986)).

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**Table B-11**  
**Chemical Properties of Hydrocarbon Constituents**

| Chemical Class        | Representative Chemical | Liquid Density (g/cm <sup>3</sup> ) @ 293 K | Henry's Law Constant (dim.) | Water Solubility (mg/l) @ 293 K | Pure Component Vapor Pressure (mm Hg) 293 K | Vapor Density (g/m <sup>3</sup> ) @ 293 K | Soil Sorption Constant (K <sub>oc</sub> ) (L/kg) @ 298 K |
|-----------------------|-------------------------|---|-----------------------------|---------------------------------|---|---|--|
| <b>n-Alkanes</b>      |                         |   |                             |                                 |   |   |  |
| C4                    |                         | 0.579                                       | 25.22                       | 61.1                            | 1560  | 4960                                      | 250  |
| C5                    | n-Pentane               | 0.626                                       | 29.77                       | 41.2                            | 424   | 1670                                      | 320  |
| C6                    | n-Hexane                | 0.659                                       | 36.61                       | 12.5                            | 121   | 570                                       | 600  |
| C7                    | n-Heptane               | 0.684                                       | 44.60                       | 2.68                            | 35.6  | 195                                       | 1300   |
| C8                    | n-Octane                | 0.703                                       | 52.00                       | 0.66                            | 10.5  | 65.6                                      | 2600   |
| C9                    | n-Nonane                | 0.718                                       | NA                          | 0.122                           | 3.2   | 22.4                                      | 5800   |
| C10                   | n-Decane                | 0.730                                       | NA                          | 0.022                           | 0.95  | 7.4                                       | 13000  |
| <b>Mono-aromatics</b> |                         |   |                             |                                 |   |   |  |
| C6                    |                         | 0.885                                       | 0.11                        | 1780                            | 75.2  | 321                                       | 38   |
| C7                    | n-Butane                | 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                                      | 1100   |
| <b>Phenols</b>        |                         |   |                             |                                 |   |   |  |
| Phenol                | Phenol                  | 1.058                                       | 0.038                       | 82000                           | 0.529                                       | 2.72                                      | 110  |
| C1-Phenols            | m-Cresol                | 1.027                                       | 0.044                       | 23500                           | 0.15  | 0.89                                      | 8.4  |
| C2-Phenols            | 2,4-Dimethylphenol      | 0.965                                       | 0.048                       | 1600                            | 0.058                                       | 0.39                                      | NA   |
| C3-Phenols            | 2,4,6-Trimethylphenol   | NA  | NA                          | NA                              | 0.012                                       | 0.09                                      | NA   |
| C4-Phenols            | m-Ethylphenol           | 1.037                                       | NA                          | NA                              | 0.08  | 0.53                                      | NA   |
| Indanol               | Indanol                 | NA  | NA                          | NA                              | 0.014                                       | 0.1                                       | NA   |
| Di-aromatics          | Naphthalene             | 1.025                                       | NA                          | 30                              | 0.053                                       | 0.37                                      | 690  |

Note:NA - Not available

dim. - dimensionless

Source: USEPA (1991d).

**Table B-12**  
**Composition of a Regular Gasoline**

| Component Number       | Chemical Formula | MW (g) | Initial       |               |
|------------------------|------------------|--------|---------------|---------------|
|                        |                  |        | Mass Fraction | 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        |
| 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        |

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**Table B-12**  
**(Concluded)**

| Component Number               | Chemical Formula | MW (g) | Initial       |               |
|--------------------------------|------------------|--------|---------------|---------------|
|                                |                  |        | Mass Fraction | Mole Fraction |
| 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        |

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**Table B-13**  
**Composition of a Weathered Gasoline**

| Component Number       | Chemical Formula | MW (g) | Initial       |               |
|------------------------|------------------|--------|---------------|---------------|
|                        |                  |        | Mass Fraction | 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         | C4H10            | 56.1   | 0.0000        | 0.0000        |
| cis-2-Butene           | C4H10            | 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        |
| 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        |

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Table B-13  
(Concluded)

| Component Number               | Chemical Formula | MW (g) | Initial       |               |
|--------------------------------|------------------|--------|---------------|---------------|
|                                |                  |        | Mass Fraction | Mole Fraction |
| 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        |

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## Appendix C Modeling

### C-1. Available Analytical and Numerical Models

Numerous analytical and digital models have been written to simulate pressure distributions, airflow, vapor transport, and extraction. In the past, many of these models were written for a specific purpose (e.g. a doctoral dissertation) and were not generally "maintained" as programs which could be easily obtained and used by design team members. Either that or many of the models were extremely complex and could only be used on a computer workstation or mainframe and consequently are not available to the typical engineer. However, advances in computing technology and software applications have enabled the development of several vadose zone multiphase models that incorporate complex mathematical solutions in a user-friendly program. Most of the well-recognized models are widely available and supported by various companies that promote environmental software. Table C-1 summarizes these soil vapor flow, contaminant transport, and extraction models, which were compiled primarily from conducting internet web searches and by including models currently being used in the field of vapor transport modeling. Each of the models presented can be run on PC system.

### C-2. Pressure Distribution/Airflow

Pressure distribution/airflow models are analogous to groundwater flow models. They are constructed in a similar fashion, and they provide similar output. The one significant difference between the two types of models is that soil vapors are compressible gases for which densities, viscosities, and gas constants can vary depending on chemical composition, temperature, and pressure. Typical input parameters for pressure distribution/airflow models are as follows:

- Air permeability of soils ( $L^2$ ).
- Flow rates from extraction points or to injection points ( $L^3/T$ ).
- Air-filled soil porosity.
- Thickness of the vadose zone ( $L$ ).
- Dynamic viscosity of vapor ( $M/L-T$ ).
- Vapor temperature (degrees).
- Pressure boundary conditions ( $M/L-T^2$ ).
- Output from pressure distribution/airflow models can include:
- Vapor pressure distributions ( $M/L-T^2$ ).

- Flow rates from constant pressure nodes ( $L^3/T$ ).
- Vapor velocities ( $L/T$ ).
- Vapor “particle” pathlines.

*a.* The models listed in Table C-1 can all be used for these simulations. Those models, which are identified in Table C-1 as having an “easy” use, can typically be used by a project engineer with a strong background in fluids and soil science or geotechnical engineering. Project engineers who have experience using groundwater flow models typically have little difficulty using the simpler pressure distribution/airflow models. However, the input parameters and output from these models are less intuitively understood than those from groundwater flow models. Thus, novice modelers should always ensure that their work receives peer review from more experienced practitioners.

*b.* In many instances the pressure gradients imposed by SVE/BV systems are not large enough to cause significant density differences in soil vapors. In these instances, many engineers simply use existing groundwater models (with corrections for air permeabilities and air heads) to simulate soil vapor systems. Massmann (1989) provides an excellent description of the technique including detailed instructions and an analysis of limitations.

### **C-3. Coupled Fluid Flow and Contaminant Transport Models**

Coupled fluid flow and contaminant transport models include airflow/contaminant transport models and multiphase flow/contaminant transport models. Both types involve two steps: solution of fluid flow equations to obtain fluid velocities, and solution of advection-dispersion equations to obtain contaminant concentrations. Most models including an airflow component involve solution by finite-difference or finite-element methods. These methods involve discretization of the model domain into nodes or cells.

*a.* For airflow and contaminant transport models, the pressure distribution is calculated by solution of the partial differential equation for airflow. Flow velocity is calculated using the pressure distribution in conjunction with Darcy's law. Each node (or cell) of the model includes a source/sink term, representing contaminants released or absorbed over time. The source/sink term may include equilibrium relations for volatilization/dissolution, sorption/desorption, and degradation. Vapor phase concentrations are calculated using mass balance relations in conjunction with the advection-dispersion equation. If high flow velocities are anticipated, dispersion may be neglected due to the predominance of advective transport.

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Table C-1

## Summary of Pressure Distribution, Airflow, and Vapor Transport Models for PCs

| Model Name      | Model Type and Use   | Developer and Availability   | Computer Requirements   | Input Parameters   | Output Parameters  | Ease of Use |
|-----------------|--|--|---|--|--|-------------|
| AIRFLOW/<br>SVE | 2-D finite element radial symmetric airflow  | Scientific Software Group<br>Phone (703) 620-9214  | IBM PC 386/486 with minimum of 4Mb RAM, EGA or VGA display, and a math coprocessor. A mouse is recommended.   | Permeability, initial pressures, gas characteristics, temperature  | Soil pressure distribution, total system flow  | Easy        |
| AIR2D,<br>AIR3D | 2-D and 3-D analytical radial-symmetric airflow  | U.S. Geological Survey<br>810 Bear Tavern Road,<br>Suite 206<br>West Trenton, NJ 08628<br>Phone: (609)-771-3901    | IBM PC/AT compatible,<br>512K RAM   | Permeability test data, initial pressures, flow rates  | Permeability, pressure distribution and flow   | Easy        |
| BIOSLURP        | 2-D multiphase hydrocarbon vacuum enhanced recovery & transport model  | Draper Aden Environmental Modeling, Inc.<br>2206 S. Main St.<br>Blacksburg, VA 24060<br>(540) 961-DAEM             | Windows 3.x/Windows 95/Windows NT and 8 MB RAM  | Hydraulic properties, dispersivities, diffusion coefficients, biodegradation parameters, distribution coefficients, transfer rates.    | Pressure, fluid saturation, velocity, pumping/injection rates, concentrations, and mass. | Moderate    |
| BioSVE          | Screening model to simulate vacuum enhanced recovery and biodegradation.   | Draper Aden Environmental Modeling, Inc.<br>2206 S. Main St.<br>Blacksburg, VA 24060<br>(540) 961-DAEM             | Windows 3.x/Windows 95/Windows NT and 4 MB RAM  | Air pumping rate, mass, bioefficiency, volume of contaminated soil, free product recovery parameters, and species-specific properties. | Mass of species in various phases and species well gas concentration vs. time.           | Moderate    |
| Hyper-Ventilate | Screening  | Developed by: USEPA and Shell Oil Company<br><br>Available through NTIS:<br>703/487-4650<br>Order #PB-93-502664/AS | HyperVentilate v2.0 for Microsoft Windows requires 386 or higher processor, 4 MB RAM minimum, and VGA or 8514. The software requirements are DOS 3.1 or higher, or Microsoft Windows 3.1 or higher. | Permeability, porosity, initial pressures, topography, boiling point data on spill components, and desired remediation time            | Estimates of flow rates; removal rates; residual concentrations, no. of wells required   | Easy        |
| MAGNAS          | 2-D and 3-D finite element transport of water, NAPL, and air through porous media. Simulate flow of air as a fully active phase. | HydroGeologic, Inc. 1165 Hernadon Parkway, Suite 900, Hernadon, VA 22079 703/478-5186                              | IBM PC/AT compatible. Code documentation and user's manual is available. Written in FORTRAN 77.   | Heterogeneous and anisotropic media properties, capillary pressures and permeability.  | Breakthrough curves of concentration vs. time, flow and transport mass balances.         | Difficult   |

**Table C-1**  
**(Concluded)**

| Model Name | Model Type and Use  | Developer and Availability   | Computer Requirements  | Input Parameters  | Output Parameters  | Ease of Use |
|------------|---|--|--|---|--|-------------|
| MODAIR     | 2-D or 3-D finite difference predictions of airflow in unsaturated zone.                    | Scientific Software Group<br>Phone (703) 620-9214  | PC 386/486 with 2 MB RAM. Requires SURFER or other graphics package for graphical output.    | Unsaturated zone permeability, pressure conditions, vacuum rates.   | Airflow distributions, pressures, velocities.  | Moderate    |
| MOD-FLOW   | 3-D finite difference groundwater flow (converted for air flow calculations)                | U.S. Geological Survey<br>431 National Center<br>Reston, VA 20192                                      | IBM PC/AT compatible, DOS 3.3 or higher, math coprocessor, graphics monitor                  | Vapor conductivity, initial pressures   | Soil pressure distribution; total system flow  | Difficult   |
| MOFAT      | 2-D finite element multiphase flow and multicomponent transport of up to 5 species          | Draper Aden Environmental Modeling, Inc.<br>2206 S. Main St.<br>Blacksburg, VA 24060<br>(540) 961-DAEM | Windows 3.x/Windows 95/Windows NT and 8 MB RAM.  | Hydraulic properties, fluid properties, dispersivity, concentrations, partition and mass transfer coefficients. | Pressure heads, saturations, and velocities, and concentrations.                           | Moderate    |
| MOVER      | 2-D finite element multiphase areal flow with vacuum enhanced recovery model.               | Draper Aden Environmental Modeling, Inc.<br>2206 S. Main St.<br>Blacksburg, VA 24060<br>(540) 961-DAEM | Windows 3.x/Windows 95/Windows NT and 8 MB RAM.  | Initial conditions, boundary conditions, soil hydraulic properties, hydraulic conductivity, and porosity.       | Spatial distribution of fluid pressure, saturation, velocity, and pumping/injection rates. | Moderate    |
| P3DAIR     | 2-D or 3-D simulation of air flow and transport of vapor in unsaturated soils using MODFLOW | Scientific Software Group<br>Phone (703) 620-9214  | PC 486/Pentium with 2 MB RAM. Requires SURFER or other graphics package for output graphics. | Air pressure solutions from MODAIR, chemical specific parameters.   | Spatial distribution of vapor concentrations and component mass.                           | Difficult   |
| TIMES      | 2-D finite element simulations of dissolved constituents in water, airflow, and NAPL.       | TriHydro Corporation<br>(307) 745-7474   | Windows 96/Windows NT, 486 and higher, and 8MB RAM minimum                                   | Hydrogeologic and fluid characteristics, constituent specific parameters, NAPL, pumping and vacuum rates.       | Water heads, pressure distribution, constituent concentrations, and air velocities.        | Easy        |
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*b.* For multiphase flow and contaminant transport models, the air pressure distribution is calculated by simultaneous solution of air, water, and NAPL flow equations. The equations are usually solved in terms of air-water, air-NAPL, and NAPL-water capillary pressures. Fluid mass balance is maintained using capillary pressure-saturation relations, which are also used to specify air, water, and NAPL permeabilities at each node (or cell).

*c.* Fluid velocities are calculated using pressure (or head) distributions in conjunction with Darcy's law. Contaminant partitioning is specified by source/sink terms for each node, and contaminant concentrations are calculated using mass balance relations in conjunction with the advection-dispersion equation. Because of the complexity of multiphase flow models, simplifying assumptions are often used. Depending on the assumptions involved, some models may be more appropriate for NAPL or dissolved phase transport than vapor transport.

*d.* Care is advised when using coupled fluid flow and contaminant transport models. Most of these models are based upon the "local equilibrium assumption," which assumes that mass transfer to and from the air phase is instantaneous. In reality, mass transfer may be limited by diffusion or the kinetics of sorption/desorption and volatilization/dissolution. This tends to result in longer treatment times than model predictions. In addition, several model parameters may be difficult or impossible to measure (e.g., dispersivity, partitioning relations, and constitutive relations for multiphase flow). Although most of these parameters are treated as constants, some are known to vary as functions of both space and time (e.g., dispersivity). To evaluate the accuracy of model predictions, validation with field data (such as pumping tests), is recommended.

(1) Typical input parameters for coupled airflow and contaminant transport models include:

- Time stepping information.
- Bulk dry density of soil.
- Soil organic carbon content.
- Air-water, air-soil, and air-NAPL partition coefficients for each compound.
- Air permeability.
- Air-filled soil porosity.
- Volumetric moisture content of soils.
- Pumping rates at extraction points or injection points.
- Thickness and geometry of the vadose zone.
- Dynamic viscosity of vapor.
- Vapor temperature.

- Gas molar mass.
- Total mass of each compound in the system or rate of mass addition.
- Compound degradation rates.
- Air dispersion coefficients.
- Gas constant (R).
- Pressure boundary conditions.

(2) Additional parameters for multiphase flow and contaminant transport models include:

Capillary pressure-saturation relations.

Air-water, air-NAPL, and NAPL-water interfacial tensions.

Soil-water, NAPL-water, and NAPL-soil partition coefficients.

Water dispersion coefficients.

NAPL composition data.

(3) Output from fluid flow and contaminant transport models can include:

Air pressure distributions.

Flow rates at constant pressure boundaries.

Airflow velocities.

Airflow pathlines.

Mass removal rates of compounds in air.

Spatial and temporal distributions of chemical concentrations in air, soil, and water.

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**Appendix D****Recommended Estimation Methods for Air Permeability****D-1. Introduction**

Various methods used to estimate the air permeability of a given soil are summarized below. Air permeability estimates are required to predict or evaluate system performance using the available analytical and numerical models. Indirect, laboratory, and field methods for estimating air permeability are presented.

**D-2. Indirect Method**

Air permeability can be estimated as a function of saturated hydraulic conductivity. Intrinsic permeability can be obtained from the definition of saturated hydraulic conductivity as

$$k_i = \frac{K \mu}{\rho g} \quad \text{D-1}$$

where

$k_i$  = intrinsic permeability, [L<sup>2</sup>]

$K$  = saturated hydraulic conductivity, [L/T]

$\mu$  = dynamic viscosity of water, [M/L-T]

$\rho$  = density of water, [M/L<sup>3</sup>]

$g$  = gravitational constant, [L/T<sup>2</sup>]

a. The relationship between air permeability and intrinsic permeability is typically expressed as

$$k = k_i * k_{ra} \quad \text{D-2}$$

where

$k$  = air permeability

$k_i$  = intrinsic permeability

$k_{ra}$  = relative permeability to air

b. Burdine (1953) and Mualem (1976) have developed closed-form analytic solutions expressing relative permeability as a function of water content. Corey (1986b) used Burdine's solution in conjunction with the Brooks-Corey pressure-saturation relation (Brooks and Corey 1964) to develop the following expression for relative permeability to air

$$k_{ra} = (1 - S_e)^2 \left( 1 - S_e^{\frac{2+\lambda}{\lambda}} \right) \quad \text{D-3}$$

where

$S_e$  = effective water saturation

$\lambda$  = Brooks-Corey pore size distribution index

c. Effective water saturation  $S_e$  is further defined as

$$S_e = \frac{S_w - S_r}{1 - S_r} \quad \text{D-4}$$

where

$S_w$  = water saturation

$S_r$  = residual water saturation

Figure 4-2 shows the relationship between relative permeability to air and water content based on Equation D-3.

d. Thus, with estimates of the water content, residual water saturation, capillary pressure head-saturation relationship and saturated hydraulic conductivity, air permeability can be calculated as

$$k = (1 - S_e)^2 \left( 1 - S_e^{\frac{2+\lambda}{\lambda}} \right) \frac{K\mu}{\rho g} \quad \text{D-5}$$

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**D-3. Laboratory Methods**

*a. Grain size distribution.* Air permeability as a function of the average pore radius can be estimated very roughly from grain size analyses performed on soil samples using the following relationship (Massmann 1989)

$$k_i = 0.125 r^2 \quad \text{D-6}$$

where

$k_i$  = intrinsic permeability, darcies

$r$  = characteristic pore radius (mm), defined as

$$r = c D_{15} \quad \text{D-7}$$

where

$c$  = empirical constant approximately equal to 0.1 for sand and gravel

$D_{15}$  = grain size for which 15 percent by weight of particles are smaller (mm)

Combining Equations D-6 and D-7

$$k = 1,250 D_{15}^2 \quad \text{D-8}$$

*b. Column tests (e.g., permeameters).* Permeameters subjected to a pressure gradient may be used to estimate the air permeability of a given soil sample.

**D-4. Limitations of Indirect and Laboratory Methods**

In general, indirect and laboratory methods yield air permeabilities which may be suspect. This is due primarily to the following:

*a.* Samples collected from discrete depths may not be representative of the unsaturated zone as a whole. This is especially true when attempting to predict pore size distribution from grain size distribution (e.g., by the method above). Grain size data reveal little as the presence of structural features such as macropores, cracks, or thin lenses are paths of least resistance for airflow.

b. Laboratory studies such as column tests may be limited by scale dependency, and thus the results may not be readily extrapolated to a field-scale design. Similarly, column tests performed on fine grain soils such as silt and clay generally suggest that little or no airflow is possible under a variety of vacuums. However, field studies conducted on these soil types may reveal that significant airflow may be achieved due to macropores, secondary permeability zones such as fractures, and heterogeneities.

c. The presence of NAPL, which competes with water and air for pore space, may not be factored into the air permeability calculation.

d. Spatial variability in the moisture content and soil types (i.e., heterogeneities) may not adequately be accounted for in a small number of discrete samples.

e. Air permeability measurements are a function of the soil's dry bulk density, which may be altered by sample collection and repacking of soils. To the extent that adequate numbers of samples are collected and measures are taken to account for the above factors, indirect and laboratory methods can provide useful supplemental data encompassing spatial variability over a larger portion of a site than is typically possible using field methods performed at a more limited number of locations.

#### D-5. Field Methods

a. Pneumatic pump tests (air permeability tests). Pneumatic pump tests offer an alternative to indirect and laboratory methods for calculating air permeability. These tests tend to provide more realistic estimates of air permeability and are capable of characterizing a larger portion of the unsaturated zone at each test location. A number of investigators (e.g., Johnson, Kemblowski, and Colthart 1990b; McWhorter 1990; and Massmann 1989) have developed transient and steady-state solutions for airflow, which can be used for analysis of pneumatic pump test data. These solutions are described further below.

(1) Pneumatic pump tests can be conducted using extraction wells in the same manner as groundwater pump tests. Since flow equations are also available for point sinks and horizontal line sinks, extraction points or trenches can also be used. Monitoring probes are installed adjacent to the extraction vent to collect pressure data as a function of distance and time. The effects of layered heterogeneities and vertical anisotropy can be extremely important, and it is strongly recommended that they be evaluated using vertically spaced monitoring probes (multidepth probe clusters). Likewise, lateral heterogeneities and horizontal anisotropy can be evaluated using horizontally spaced monitoring probes. Ideally, horizontally spaced monitoring probes should be installed in two perpendicular directions, with spacing increasing logarithmically with distance from the vent (e.g., 0.2 m, 2 m, 20 m, etc.). The perpendicular orientation allows evaluation of anisotropy within the horizontal plane, and the logarithmic spacing allows preparation of distance-drawdown plots for evaluation of well efficiency.

(2) Although pressure measurements should be recorded at the extraction vent to evaluate well efficiency, these measurements should *not* be used for air permeability calculations. Fitting the compressible flow solution to radial distance drawdown data typically predicts measured vacuums at the extraction vent that are two to five times lower than the actual measurements at the extraction vent. This is probably the result of water buildup near the extraction vent. If the vent is screened near the water table, or if the soil moisture content exceeds residual saturation, the increase in capillary pressure caused by the induced vacuum will tend to increase water saturations. Increased water saturations will be greatest

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immediately adjacent to the vent. Figure 4-2 shows that for predominantly air-filled soils, even a slight increase in water saturation significantly reduces the air permeability. As a result, the pressure gradient and measured vacuum near the extraction well will be much higher than that predicted assuming a constant water content (McWhorter 1990).

*b. Transient solutions.* Transient solutions may be used for evaluation of low-permeability soils, or for determination of air permeability prior to redistribution of soil moisture as a result of the induced vacuum (or pressure). Rapid pressure measurements should be recorded upon startup, with measurement intervals increasing with time (e.g., 10-second intervals for the first 2 minutes, 30-second intervals for the next 8 minutes, 1-minute intervals for the next 20 minutes, and so on).

(1) The solution method should be selected based on the geometry of the vadose zone and the vent being tested. One-dimensional radial solutions should be used for fully penetrating wells in vadose zones with upper and lower impermeable boundaries (e.g., Massmann 1989; McWhorter 1990, Johnson, Kemblowski, and Colthart 1990b). These solutions can also be used for partially penetrating wells, provided that measurement points are located at least 1- times the vadose zone thickness from the extraction well.

(2) McWhorter (1990) developed an exact, quasi-analytic solution for transient one-dimensional radial flow. Although the solution has the capability to incorporate gas slippage, the analysis method outlined below assumes that the Klinkenberg factor (a measure of gas slippage) has been set equal to zero. Accordingly, McWhorter (1990) refers to air permeability as the apparent gas permeability.

(3) McWhorter's solution is applied by preparing a graph of  $(P/P_{atm})^2$  versus  $\ln(r^2/t)$ , where P is the absolute pressure measured at distance  $r$ ,  $P_{atm}$  is atmospheric pressure, and  $t$  is time since the start of the test. The slope of the line is then used to calculate the apparent gas permeability using the equation

$$k_a = - \frac{RT \mu Q_m}{2 \pi b M P_{atm}^2 slope} \quad D-9$$

where

$k_a$  = apparent gas permeability reflecting the air-filled and not the water-filled pore space

$R$  = gas constant

$T$  = absolute temperature

$Q_m$  = mass flow rate

$b$  = unsaturated zone thickness

$M$  = molecular weight

(4) Johnson, Kemblowski, and Colthart (1990b) developed an approximate solution for transient radial two-dimensional flow by linearizing the partial differential equation (PDE) for transient flow (see paragraph 2-4d).

(5) As described in paragraph 2-4c, the solution to the linearized PDE for a constant sink at  $r = 0$ , with  $P = P_{atm}$  at  $r = 4$ , is (Johnson et al. 1990b):

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} \int_u^{\infty} \frac{e^{-x}}{x} dx \quad \text{D-10}$$

where

$P$  = absolute pressure [M/LT<sup>2</sup>]

$P_{atm}$  = atmospheric pressure [M/LT<sup>2</sup>]

$Q_v$  = volumetric flow rate [L<sup>3</sup>/T]

$\mu$  = dynamic viscosity [M/LT<sup>2</sup>]

$b$  = the thickness of the vadose zone or stratum of interest [L]

$x$  = a dummy variable of integration, and

$$u = \frac{r^2 n_a \mu}{4 k_a P_{atm} t} \quad \text{D-11}$$

where

$r$  = radial distance [L]

$n_a$  = air-filled porosity [L<sup>3</sup>/L<sup>3</sup>]

$t$  = time

(6) Equation D-10 is sometimes written as

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} W(u) \quad \text{D-12}$$

where  $W(u)$  is the Theis well function. Equation D-12 can be solved for air permeability as:

$$k_a = \frac{Q_v \mu W(u)}{4 \pi b k_a (P - P_{atm})} \quad \text{D-13}$$

and Equation D-11 can be solved for air-filled porosity as:

$$n_a = \frac{4 k_a P_{atm} t}{r^2 \mu} u \quad \text{D-14}$$

(7) By fitting a log-log plot of  $P - P_{atm}$  versus time to the Theis "type curve" ( $W(u)$  vs.  $1/u$ ), a point along the type curve can be selected where values of  $P - P_{atm}$  and  $t$  correspond to a particular  $u$  and  $W(u)$ . These values can be substituted into Equations D-13 and D-14 to obtain values of air permeability and air-filled porosity.

(8) In a similar manner, plots of  $P - P_{atm}$  versus time can be fitted to type curves for the leaky well function (paragraph 2-4c) to obtain values of air permeability, air-filled porosity, and the vertical air permeability of a leaky confining layer.

(9) The Cooper-Jacob approximation offers a somewhat simpler method for analysis of transient air permeability test data (paragraph 2-4c). The Cooper-Jacob approximation applies when  $u \leq 0.01$  (i.e., small radial distances or large values of time), and is written as:

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} \left( \ln \frac{4 k_a P_{atm} t}{r^2 n_a \mu} - 0.5772 \right) \quad \text{D-15}$$

(10) When  $u \neq 0.01$ , a plot of pressure vs  $\ln(t)$  should show a straight line with slope:

$$m = \frac{Q_v \mu}{4 \pi b k_a} \quad \text{D-16}$$

where

$m$  = the change in pressure over one log cycle

(11) The time intercept when  $P - P_{atm} = 0$  should occur is:

$$\ln \frac{4 k_a P_{atm} t_o}{r^2 n_a \mu} = 0.5772 \quad \text{D-17}$$

where

$t_o$  = the time intercept when  $P - P_{atm} = 0$

(12) Equation D-16 can be rearranged in terms of air permeability:

$$k_a = \frac{Q_v \mu}{4 \pi b m} \quad \text{D-18}$$

(13) Likewise, equation D-17 can be solved for the air-filled porosity:

$$n_a = 2.25 \frac{k_a P_{atm} t_o}{r^2 \mu} \quad \text{D-19}$$

c. Steady state solutions. Steady state solutions can be used for air permeability tests, provided that sufficient time is allowed for flow to stabilize. Estimates of the length of time necessary to reach steady-state for one-dimensional radial flow can be developed by noting that the slope of the Theis type curve is small for  $u \neq 0.01$ , indicating that there is little change in  $P - P_{atm}$  over time. By choosing a point on the Theis type curve (or leaky type curves, if used) where further changes in  $W(u)$  are considered negligible, the time to reach steady state can be calculated according to:

$$t = \frac{r^2 n_a \mu}{4 k_a P_{atm} \epsilon} \quad \text{D-20}$$

where

$\epsilon$  = the value of  $u$  for which further changes in  $W(u)$  are considered negligible

(1) For some conditions, steady state solutions may provide a better estimate of air permeability than transient methods. These conditions include sites with an unsealed ground surface, or where applied vacuums (or pressures) are greater than 0.2 atmospheres. Although transient test data from sites with leaky surface covers can be evaluated using the leaky well function, this analysis treats air as an incompressible fluid. In contrast, steady state solutions treat air as a compressible fluid. As shown by Massmann (1989), these effects are significant for applied vacuums greater than 0.2 atmospheres, gauge.

(2) For the case of one-dimensional radial flow, steady state solutions can also be used to analyze transient permeability test data, provided that  $u \neq 0.01$ . This condition is known as the pseudo-steady state (McWhorter and Sunada 1977), and is described in paragraph 2-4d.

(3) For one-dimensional radial flow, the steady state solution is given by Equation 2-20. This equation can be written for two discrete measurement points as:

$$k_a = \frac{Q_v P^* \mu \ln(r_2/r_1)}{\pi b (P_1^2 - P_2^2)}$$

D-21

where

$Q_v$  = volumetric flow rate [ $L^3/T$ ] (extraction flow is considered to be negative)

$P^*$  = pressure at the point of flow measurement [ $M/LT^2$ ]

$r_1, r_2$  = radial distance to observation points [ $L$ ]

$P_1, P_2$  = absolute pressures at observation points [ $M/LT^2$ ]

(4) Since the vacuums measured at extraction wells are commonly exaggerated by reduced well efficiency, these data should not be used for determination of air permeability. However, in conjunction with wellbore vacuums calculated using Equation 2-20, these data can be used to calculate well efficiency via Equation 4-6.

(5) A steady state solution for two-dimensional radial flow is given in Equation D-22 below (see paragraph 2-4c).

(6) Equation D-22 can be used to determine the horizontal and vertical air permeability using methods outlined by Shan, Falta, and Javandel (1992), or computer programs can be used to fit field data to Equation D-22 as a function of horizontal and vertical air permeability. The vertical air permeability can be determined by scaling the horizontal coordinate axis ( $r$ ) using Equation E-8 until the best fit of field data is obtained. The vertical air permeability can then be determined from the horizontal air permeability and the appropriate scaling factor. An example of field data fitted to Equation D-22 is shown in Figures D-1 and D-2.

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L-l)} \left[ \ln \left( \frac{z-l + \sqrt{r^2 + (z-l)^2}}{z-l + \sqrt{r^2 + (z-l)^2}} \cdot \frac{z+L + \sqrt{r^2 + (z+L)^2}}{z+l + \sqrt{r^2 + (z+l)^2}} \right) - \sum_{n=1}^{\infty} (-1)^n \ln \left( \frac{z-2nb+L + \sqrt{r^2 + (z-2nb+L)^2}}{z-2nb+l + \sqrt{r^2 + (z-2nb+l)^2}} \cdot \frac{z-2nb-L + \sqrt{r^2 + (z-2nb-L)^2}}{z-2nb-l + \sqrt{r^2 + (z-2nb-l)^2}} \cdot \frac{z+2nb-L + \sqrt{r^2 + (z+2nb-L)^2}}{z+2nb+l + \sqrt{r^2 + (z+2nb+l)^2}} \right) \right] \quad D-22$$

*d. Automated Permeability Analysis Tools.* Falta (1996) presents software, GASSOLVE, that analyzes soil air permeability using transient or steady-state pressure/vacuum data collected during a field test. The software implements solutions for compressible airflow to a partially (or fully) penetrating well. A multi-dimensional non-linear optimization routine inverts the pressure data from multiple observation wells to determine air permeability. The software allows the user to specify the surface boundary condition as open (uncovered and allowing a direct communication between the atmosphere and the subsurface), leaky (surface covering or shallow strata that inhibits, but does not prevent, the communication with the atmosphere), or fully covered (no communication due to a tight seal such as a geomembrane). The software is a simple DOS program that uses ASCII text input files. When preparing the input file, the user can import well/time/vacuum data from another ASCII file or can enter the data manually. The software output includes the horizontal air permeability and, if a open site is assumed, and the vertical permeability of the soil. If a leaky surface is assumed, the program also computes a leakage value. The program also compares the predicted vacuum/pressure at each monitoring point to the observed values and computes the residual sum of squares and a total average error as a measure of the goodness of fit. The GASSOLVE software is available from the USACE HTRW CX (DoD staff and contractors only) or Dr. Falta at Clemson University.

*e. Soil gas tracer studies.*

(1) Soil gas tracer studies rely on the use of conservative gases which are injected into the subsurface through wells. The tests provide a method to calculate the breakthrough of a given gas as a function of the subsurface conditions (i.e., air permeability). The tests can be performed either under a natural or forced gradient. The selection of a suitable gas for a tracer study is dependent upon the properties of the gas and the availability of instrumentation for detecting the injected gas. A number of potential tracers have been cited in the literature, including sulfur hexafluoride, helium, methane, and argon.

(2) Tracer studies provide not only an estimate of the air permeability, but also provide empirical data on the pore volume exchange rate which is used to optimize the SVE/BV operation. The apparent vapor velocity can be calculated by dividing the distance between the tracer gas injection and detection points by the elapsed time from injection of the tracer gas to the appearance of the center of mass of the tracer slug at the detection point. By injecting tracer gas at one monitoring point at a time and detecting the arrival of the tracer at the test vent, an assessment of the anisotropy of a site can be made (Marley 1993).

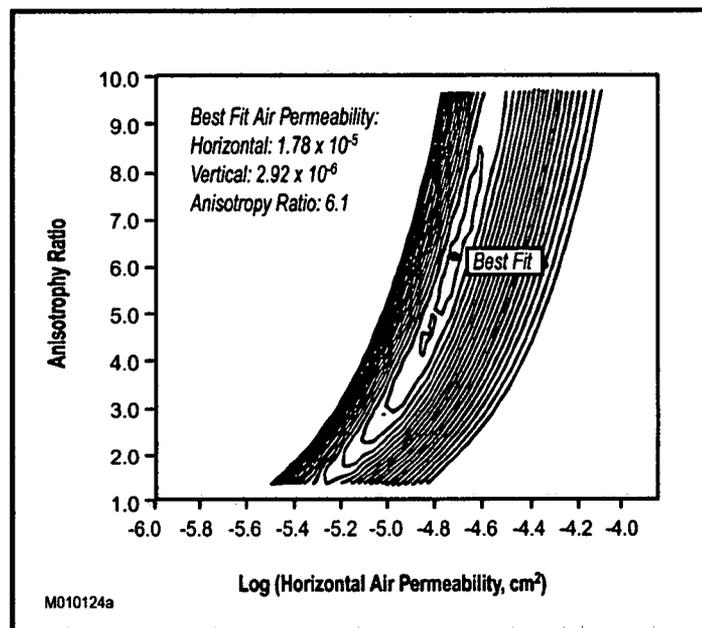


Figure D-1 Best fit of field data using Equation D-22

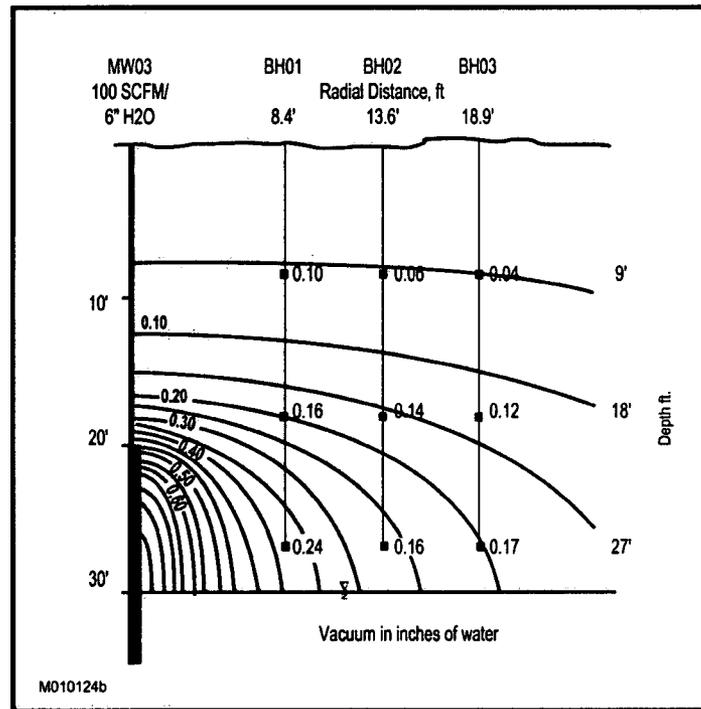


Figure D-2. Pressure isobars calculated using Equation D-22 and best-fit air permeabilities from Figure D-1.

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**Appendix E****Analytical Solution For Two-Dimensional Flow To A Well****E-1. Introduction**

An analytical solution for two-dimensional flow to a well can be obtained by superposition of a point sink solution along the length of the well screen.

An equation for two-dimensional radial flow can be expressed as

$$\frac{\partial^2 P^2}{\partial r^2} + \frac{1}{r} \frac{\partial P^2}{\partial r} + \frac{\partial^2 P^2}{\partial z^2} = 0 \quad (\text{E-1})$$

where

$r$  = the horizontal radial coordinate (equivalent to  $[x^2 + y^2]^{1/2}$  in cartesian coordinates)

$z$  = the vertical radial coordinate (equivalent to the vertical cartesian coordinate)

The solution to this equation for a point sink located at  $r = 0, z = z'$  in an infinite space, is

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2 \pi k_a} \frac{1}{\sqrt{r^2 + (z - z')^2}} \quad (\text{E-2})$$

where

$z'$  =  $z$ -coordinate of the point sink

The point sink solution can be integrated with respect to  $z$  to obtain a line sink solution in an infinite space

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2 \pi k_a (L - l)} \ln \left\{ \frac{z - l + \sqrt{r^2 + (z - l)^2}}{z - L + \sqrt{r^2 + (z - L)^2}} \right\} \quad (\text{E-3})$$

where

$l$  =  $z$ -coordinate of the top of the well screen

$L$  =  $z$ -coordinate of the bottom of the well screen

## E-2. Superposition to model the effects of atmospheric and impermeable boundaries

a. The effects of atmospheric and impermeable boundaries can be simulated using the method of images. Recognizing  $P^2 - P_{atm}^2$  as a Laplace potential, an atmospheric boundary at  $z = 0$  can be simulated by adding the potential from an image source located  $r = 0, z = -l$  to  $L$  to that from a real sink located at  $r = 0, z = l$  to  $L$  (Figure E-1)

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L-l)} \ln \left( \frac{z-l + \sqrt{r^2 + (z-l)^2}}{z-L + \sqrt{r^2 + (z-L)^2}} \cdot \frac{z+L + \sqrt{r^2 + (z+L)^2}}{z+l + \sqrt{r^2 + (z+l)^2}} \right) \quad (E-4)$$

Likewise, the water table can be simulated with an image sink/source pair located at  $r = 0, z = 2b - L$  to  $2b - l$  and  $r = 0, z = 2b + l$  to  $z = 2b + L$

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L-l)} \left\{ \begin{array}{l} \ln \left( \frac{z-l + \sqrt{r^2 + (z-l)^2}}{z-L + \sqrt{r^2 + (z-L)^2}} \cdot \frac{z+L + \sqrt{r^2 + (z+L)^2}}{z+l + \sqrt{r^2 + (z+l)^2}} \right) \\ + \ln \left( \frac{z-2b+L + \sqrt{r^2 + (z-2b+L)^2}}{z-2b+l + \sqrt{r^2 + (z-2b+l)^2}} \cdot \frac{z+2b+l + \sqrt{r^2 + (z+2b+l)^2}}{z+2b+L + \sqrt{r^2 + (z+2b+L)^2}} \right) \end{array} \right\} \quad (E-5)$$

which requires a corresponding sink/source pair at  $r = 0, z = -2b + L$  to  $-2b + l$ , and  $r = 0, z = -2b - l$  to  $-2b - L$

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L-l)} \left\{ \begin{array}{l} \ln \left( \frac{z-l + \sqrt{r^2 + (z-l)^2}}{z-L + \sqrt{r^2 + (z-L)^2}} \cdot \frac{z+L + \sqrt{r^2 + (z+L)^2}}{z+l + \sqrt{r^2 + (z+l)^2}} \right) \\ + \ln \left( \frac{z-2b+L + \sqrt{r^2 + (z-2b+L)^2}}{z-2b+l + \sqrt{r^2 + (z-2b+l)^2}} \cdot \frac{z-2b-L + \sqrt{r^2 + (z-2b-L)^2}}{z-2b-l + \sqrt{r^2 + (z-2b-l)^2}} \right) \\ - \ln \left( \frac{z+2b-l + \sqrt{r^2 + (z+2b-l)^2}}{z+2b-L + \sqrt{r^2 + (z+2b-L)^2}} \cdot \frac{z+2b+l + \sqrt{r^2 + (z+2b+l)^2}}{z+2b+L + \sqrt{r^2 + (z+2b+L)^2}} \right) \end{array} \right\} \quad (E-6)$$

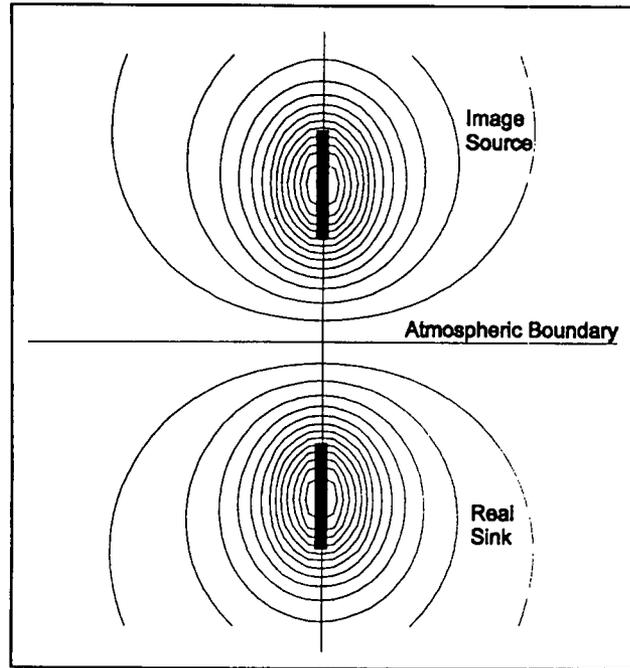


Figure E-1. Use of superposition to simulate an atmospheric boundary

More generally, each source added to balance the pressures across one boundary (e.g., the water table) produces an imbalance of pressures across the other boundary (e.g., the ground surface). As a result, additional sources and sinks are required until the incremental pressures are negligible (see Equation E-7). This is equivalent to the pressure solution obtained by Shan et al. (1992). The series summations converge in about 10 or 20 terms, and the solution can be readily evaluated on a small computer. Shan et al. (1992) provide the solution in dimensionless form, allowing application to a particular field problem through a simple scaling procedure. A plot of pressure isobars generated using Equation E-7 is shown on Figure E-2. King (1968) solved the same problem using the Dirac delta function, resulting in a slightly more complicated solution.

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2 \pi k_a (L-l)} \left[ \ln \left( \frac{z-l + \sqrt{r^2 + (z-l)^2}}{z-L + \sqrt{r^2 + (z-L)^2}} \cdot \frac{z+L + \sqrt{r^2 + (z+L)^2}}{z+l + \sqrt{r^2 + (z+l)^2}} \right) - \sum_{n=1}^{\infty} (-1)^n \ln \left( \frac{z-2nb+L + \sqrt{r^2 + (z-2nb+L)^2}}{z-2nb+l + \sqrt{r^2 + (z-2nb+l)^2}} \cdot \frac{z-2nb-L + \sqrt{r^2 + (z-2nb-L)^2}}{z-2nb-l + \sqrt{r^2 + (z-2nb-l)^2}} \cdot \frac{z+2nb-L + \sqrt{r^2 + (z+2nb-L)^2}}{z+2nb-l + \sqrt{r^2 + (z+2nb-l)^2}} \cdot \frac{z+2nb+L + \sqrt{r^2 + (z+2nb+L)^2}}{z+2nb+l + \sqrt{r^2 + (z+2nb+l)^2}} \right) \right] \quad (E-7)$$

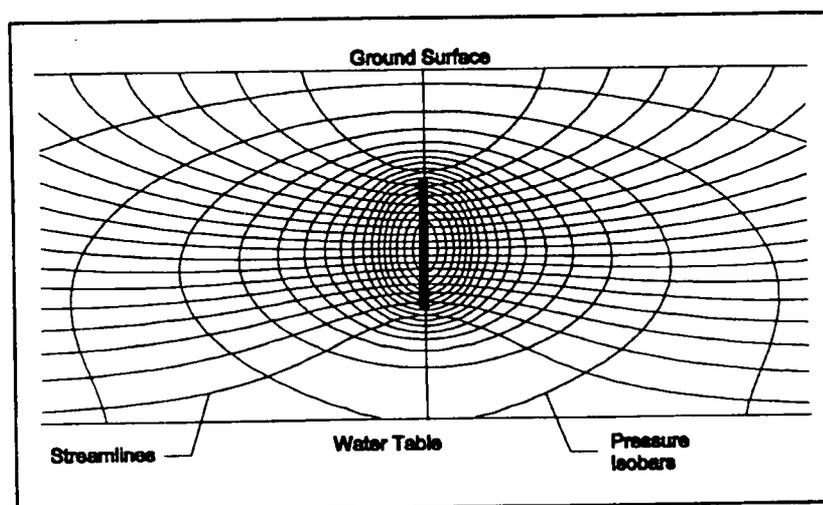


Figure E-2. Streamlines and pressure isobars

b. As described in Chapter 2, flow in anisotropic systems is governed by Equation 2-14. In order to solve this equation using the Laplace equation (Equation 2-15), it is necessary to transform the anisotropic system into an equivalent isotropic system. This can be accomplished by choosing a coordinate system parallel to the directions of maximum and minimum air permeability (the principal directions of the air permeability tensor), and performing the coordinate transformation

$$\begin{aligned} r' &= r \sqrt{\frac{k_z}{k_r}}; \\ z' &= z \end{aligned} \quad (\text{E-8})$$

Air flow equations (e.g., Equation E-7) can be solved in the transformed coordinate system using a transformed air permeability

$$k' = \sqrt{k_r \bullet k_z} \quad (\text{E-9})$$

at which point the resulting pressure (or stream function) values can be translated back into the original coordinate system using Equations E-8.

c. The principle of superposition also permits evaluation of multiple well systems. For horizontal flow between upper and lower impermeable boundaries, the pressure distribution resulting from multiple fully penetrating wells is obtained by superposition of Equation E-10

$$P^2 - P_{atm}^2 = \sum_{i=1}^n \frac{Q_i P_i \mu}{\pi b k_a} \ln \frac{r_{ei}}{\sqrt{(x - x_i)^2 + (y - y_i)^2}} \quad (\text{E-10})$$

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where

 $n$  = number of wells $Q_i$  = volumetric flow rate from the  $i^{\text{th}}$  well [ $L^3/T$ ] $P_i$  = reference pressure for the  $i^{\text{th}}$  flow rate [ $M/LT^2$ ] $r_{ei}$  = radius of pressure influence for the  $i^{\text{th}}$  well [ $L$ ] $x_i$  =  $x$ -coordinate of the  $i^{\text{th}}$  well $y_i$  =  $y$ -coordinate of the  $i^{\text{th}}$  well

Similarly, for three-dimensional flow between an upper atmospheric boundary and a lower impermeable boundary, the pressure distribution resulting from multiple partially penetrating wells is obtained by superposition of Equation E-7

$$P^2 - P_{\text{atm}}^2 = \sum_{i=1}^m \frac{Q_i P_i^* \mu}{2\pi k_a (L_i - l_i)}$$

$$\left[ \begin{aligned} & \ln \left[ \frac{(z - l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - l_i)^2})}{(z - L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - L_i)^2})} \right] \\ & \cdot \left[ \frac{z + L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + L_i)^2}}{z + l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + l_i)^2}} \right] \\ & - \sum_{n=1}^{\infty} (-1)^n \ln \left[ \frac{z - 2nb + L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb + L_i)^2}}{z - 2nb + l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb + l_i)^2}} \right] \\ & \cdot \left[ \frac{z - 2nb - L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb - L_i)^2}}{z - 2nb - l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb - l_i)^2}} \right] \\ & \cdot \left[ \frac{z + 2nb - L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb - L_i)^2}}{z + 2nb - l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb - l_i)^2}} \right] \\ & \cdot \left[ \frac{z + 2nb + L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb + L_i)^2}}{z + 2nb + l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb + l_i)^2}} \right] \end{aligned} \right] \quad (\text{E-11})$$

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where

$l_i$  = depth to the top of the well screen at the  $i^{\text{th}}$  well

$L_i$  = depth to the bottom of the well screen at the  $i^{\text{th}}$  well

$m$  = number of wells

A plot of pressure isobars generated using Equation E-11 is shown on Figure E-3.

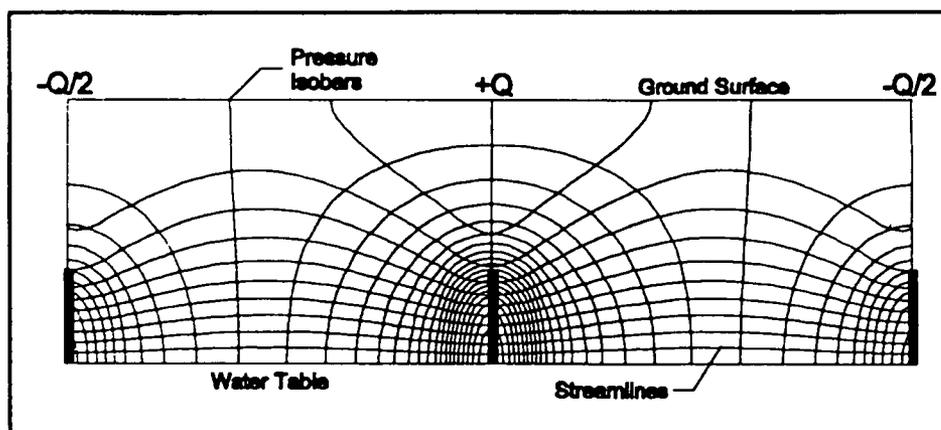


Figure E-3. Streamlines and pressure isobars for a multiwell system

*d.* As indicated previously (paragraph 2-4c(4)), both stream functions and potential functions satisfy the Laplace equation. This arises from a set of equations known as the Cauchy-Riemann equations, which apply to functions satisfying the Laplace equation. In two-dimensional Cartesian coordinates, the Cauchy-Riemann equations can be written as:

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}; \quad \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x} \quad (\text{E-12})$$

where

$\Phi$  = Laplace potential

$\psi$  = stream function

Recognizing  $P^2 - P_{\text{atm}}^2$  as a Laplace potential, stream functions can be obtained by performing the integration:

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$$\psi = \int \frac{\partial (P^2 - P_{atm}^2)}{\partial y} dx \quad (E-13)$$

Stream functions are useful for evaluating flow paths and travel times for vapor flow. Applying Equation E-13 to the equation for one-dimensional radial flow (Equation E-10) in Cartesian coordinates yields:

$$\psi = \frac{Q_v P^* \mu}{\pi b k_a} \tan^{-1} \left( \frac{y - y_1}{x - x_1} \right) + C_1 \quad (E-14)$$

where

$C_1$  = a constant of integration

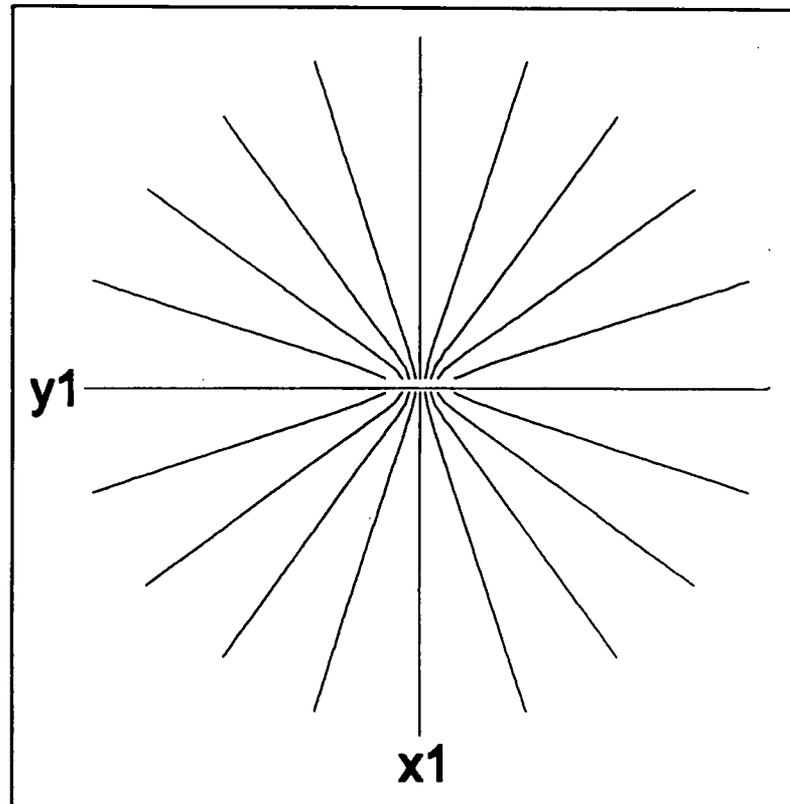


Figure E-4. Streamlines for one-dimensional radial flow

Equation E-14 represents a family of straight lines passing through  $(x_1, y_1)$ , where the arctangent term is equivalent to the angle  $\theta$  (in radians) between each line and the positive x-axis (Figure E-4).

Defining the angle  $\theta$  as:

$$\theta = \tan^{-1} \left| \frac{y - y_1}{x - x_1} \right| \quad (\text{E-15})$$

unique values of  $\psi$  can be specified for all  $\theta$  by defining the constant of integration so as:

$$\begin{aligned} \psi &= \frac{Q_v P^* \mu}{\pi b k_a} \theta \quad \text{for } 0 < \theta < \frac{\pi}{2}; \\ \psi &= \frac{Q_v P^* \mu}{\pi b k_a} (\pi - \theta) \quad \text{for } \frac{\pi}{2} < \theta < \pi; \\ \psi &= \frac{Q_v P^* \mu}{\pi b k_a} (\pi + \theta) \quad \text{for } \pi < \theta < \frac{3\pi}{2}; \\ \psi &= \frac{Q_v P^* \mu}{\pi b k_a} (2\pi - \theta) \quad \text{for } \frac{3\pi}{2} < \theta < 2\pi \end{aligned} \quad (\text{E-16})$$

In two-dimensional radial coordinates, the Cauchy-Rieman equations can be written as:

$$\frac{\partial \psi}{\partial z} = r \frac{\partial \phi}{\partial r}; \quad \frac{\partial \psi}{\partial r} = -r \frac{\partial \phi}{\partial z} \quad (\text{E-17})$$

Applying Equation E-17 to the equation for two-dimensional radial flow (Equation E-7) yields:

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$$\psi = \frac{Q_v P^* \mu}{2\pi k_a (L-l)} r \bullet$$

$$\left[ \begin{aligned} & \left[ \frac{r - (z-L) + \sqrt{r^2 + (z-L)^2}}{r + (z-L) + \sqrt{r^2 + (z-L)^2}} - \frac{r - (z-l) + \sqrt{r^2 + (z-l)^2}}{r + (z-l) + \sqrt{r^2 + (z-l)^2}} \right. \\ & \left. - \frac{r - (z+L) + \sqrt{r^2 + (z+L)^2}}{r + (z+L) + \sqrt{r^2 + (z+L)^2}} + \frac{r - (z+l) + \sqrt{r^2 + (z+l)^2}}{r + (z+l) + \sqrt{r^2 + (z+l)^2}} \right] \\ & - \sum_{n=1}^{\infty} (-1)^n \left[ \frac{r - (z-2nb+L) + \sqrt{r^2 + (z-2nb+L)^2}}{r + (z-2nb+L) + \sqrt{r^2 + (z-2nb+L)^2}} - \frac{r - (z-2nb+l) + \sqrt{r^2 + (z-2nb+l)^2}}{r + (z-2nb+l) + \sqrt{r^2 + (z-2nb+l)^2}} \right. \\ & \left. + \frac{r - (z-2nb-L) + \sqrt{r^2 + (z-2nb-L)^2}}{r + (z-2nb-L) + \sqrt{r^2 + (z-2nb-L)^2}} - \frac{r - (z-2nb-l) + \sqrt{r^2 + (z-2nb-l)^2}}{r + (z-2nb-l) + \sqrt{r^2 + (z-2nb-l)^2}} \right] \\ & - \frac{r - (z+2nb+L) + \sqrt{r^2 + (z+2nb+L)^2}}{r + (z+2nb+L) + \sqrt{r^2 + (z+2nb+L)^2}} + \frac{r - (z+2nb+l) + \sqrt{r^2 + (z+2nb+l)^2}}{r + (z+2nb+l) + \sqrt{r^2 + (z+2nb+l)^2}} \\ & \left. + \frac{r - (z+2nb-L) + \sqrt{r^2 + (z+2nb-L)^2}}{r + (z+2nb-L) + \sqrt{r^2 + (z+2nb-L)^2}} - \frac{r - (z+2nb-l) + \sqrt{r^2 + (z+2nb-l)^2}}{r + (z+2nb-l) + \sqrt{r^2 + (z+2nb-l)^2}} \right] \end{aligned} \right] \quad (E-18)$$

Equation E-18 is equivalent to the stream function obtained by Shan, Falta, and Javandel (1990). A plot of streamlines generated using Equation E-18 is shown in Figure E-2.

As described in paragraph E-2c, stream functions for multiple well systems can be evaluated by superposition of Equation E-16 or E-18. A plot of streamlines for a multiple well system is shown in Figure E-3.

## Appendix F

### Overview of Rebound Test Procedures and Data Evaluation

#### F-1. Introduction

##### a. Purpose

This appendix lays out a theoretical and practical framework for the collection and evaluation of data during rebound testing. As mentioned in Section 9-9, rebound tests (also known as "pulsing tests") are commonly used to assess the attainment of cleanup in the vadose zone. However, little information is available to guide field practitioners through the data collection and its interpretation (Holbrook et al., 1998). The objective of this appendix is to fill this void by providing a step-by-step approach to planning and performing a rebound test along with straightforward mathematical techniques for evaluating the data to determine adequacy of cleanup. The material presented in this appendix is intended to be an introduction to rebound testing and serves as a practical starting point for further development of this important procedure.

##### b. Background

The intent of rebound testing is to assess residual contamination remaining in soils after a period of active remediation. The underlying premise is that soils are inherently heterogeneous and may often be divided into two relative categories: low permeability and high permeability. During soil vapor extraction, vapors flow predominantly in the high permeability soils intersected by extraction wells and contaminant removal is primarily from these soils. This extraction creates a difference, or gradient, in the concentration between more permeable and less permeable soils. Contaminants residing in the less permeable soils are removed only after migrating into more permeable soils where soil vapors are flowing (DiGiulio et al., 1998). The migration occurs primarily by vaporous diffusion into active flow paths caused by the concentration gradient. Similar contaminant transport occurs during bioventing. During a period of rebound (i.e., no extraction or injection), the soil vapors are relatively dormant and contaminant concentrations equilibrate between phases and soil types. In other words, the air is not moving and contaminant vapors diffuse from lesser to more permeable soils and the vapor concentration in the more permeable soils approaches that of the low permeability soils. The vapor concentration in the more permeable soils can be measured periodically in the extraction wells to track the progress of rebound. Hence, the goal of a rebound test is to measure the concentration remaining in the least permeable soils by allowing equilibration of contaminant vapors among all soil types at a site. A measure of the concentration in less permeable soils is a strong indicator of the residual contamination at the site.

##### c. Introductory Example

Consider an SVE site with a single extraction well in the middle of a vapor plume within which no NAPL exists. Assume a uniform extraction rate has been drawn from the well since the initiation of operation except for two periods of dormancy. Measurements of the vapor concentration within the extraction well are illustrated in Figure F-1.

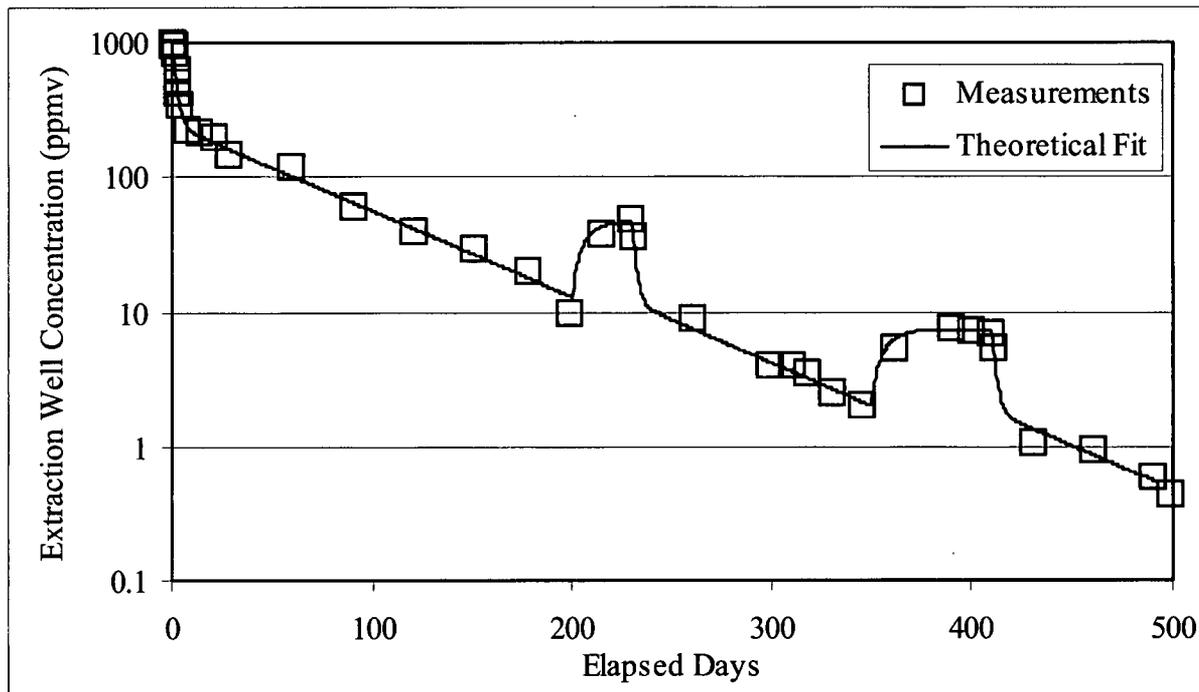


Figure F-1 Typical vapor concentration history during SVE with two rebound periods

In the example of Figure F-1, the extraction well concentration decays rapidly during the first two weeks of operation following an exponential trend. This period represents the time required to sweep the initial contaminant vapors found in the more permeable soil intervals. Beyond the first two weeks, the concentration decay follows a much slower exponential rate (i.e., notice the change in slope in the theoretical fit around Day 15). This slower rate corresponds to the rate of mass transfer from less permeable soils to more permeable soils. During this slower rate of decay, the process is often referred to as "asymptotic" with the asymptote being zero. In this example, a rebound period of 30 days was undertaken after 200 days of extraction to assess a hypothetical cleanup goal of 10 parts per million by volume (ppmv) throughout the site. Concentrations measured in the extraction well during this dormancy period revealed an increasing trend above the cleanup goal as contaminants diffused out of the less permeable soils and into the more permeable soils. Extraction was re-started at Day 230 before an equilibrium concentration had been reached. The concentration again decayed rapidly and the previous slow decay was re-established. A second rebound period was initiated at Day 350 and lasted 60 days. The 60-day period was sufficient to establish an equilibrium concentration less than the goal of 10 ppmv. The hypothetical system was operated an additional 90 days while closure reports were prepared and accepted. This example illustrates the simplest implementation and interpretation of SVE and rebound data. Many complexities arise when multiple extraction wells are operated, multiple contaminants are present, or the actual center of mass of the initial vapor plume is not known. The concepts in this appendix should provide a starting point for discussion and interpretation of results from more complex situations.

## F-2. Theoretical Framework

As described in the previous section, soils are often divided into two categories for remediation: low permeability and high permeability, relative to each other. Early models of pump-and-treat referred to the relatively low permeability soil as "immobile" since the water in the soil was practically stagnant (see Brusseau, 1991 for a review). Recent work has applied the approach to soil vapor extraction (Kaleris and Croise, 1999) and air sparging (Rabideau and Blayden, 1998). The higher permeability soil is named "mobile" since the majority of flow occurs in these soils. In the vadose zone, the mobile soils are the most permeable and appreciable air flow through these soils is induced when a practical pressure gradient is applied (e.g., air injection or extraction in a well). Immobile soils have relatively low permeabilities and air flow through these soils during the application of a pressure gradient is considered negligible. Contaminant transport in immobile soils is dominated by diffusion in the vapor phase or liquid advection and diffusion if moisture contents are high.

As described in the previous example of SVE (see Figure F-1), the initial decay in contaminant concentration in the extraction well is governed by the transport of contaminants in flowing vapors through the mobile soils and is typically on the order of days or weeks. In the immobile soils, contaminant transport occurs on a time scale proportional to the diffusion rate and the length scale associated with the immobile soil (e.g., the thickness of a clay lens) and is typically on the order of months or years. Because of these disparate time scales, the concentration in the mobile soils (equivalent to the extracted concentration during SVE) falls much faster than the concentration in the immobile soils. Contaminant removal from the immobile soils relies on diffusion of contaminants to the interface with mobile soils where the contaminants are swept to extraction wells. Hence the concentrations in the mobile and immobile soils are in dis-equilibrium and define the macro-scale mass transfer constraint resulting from soil heterogeneities. This section develops mathematical relationships describing SVE using mass balances which can be employed to analyze rebound data and estimate field-scale mass transfer constraints. The mass transfer constraints for various physical phenomena and length scales are lumped into a single, average mass transfer coefficient assumed relatively constant over time.

Consider the total mass of contaminant,  $m_j$ , in a given volume,  $V$ , of soil type  $j$  where  $j$  can signify either "m" for mobile or "i" for immobile. The total contaminant mass in the soil is equal to the sum of the mass adsorbed, the mass dissolved in pore water, and the mass volatilized:

$$m_j = C_{w,j} [(1-\phi_j) \rho_{s,j} K_{d,j} + \phi_j S_j + \phi_j (1-S_j) H] f_j V$$

$$m_j = C_{v,j} \phi_j (1-S_j) f_j V R_j \quad (F-1)$$

The parameters are defined by:

- $C_{w,j}$  = mass of contaminant per unit volume of pore water in soil type  $j$
- $C_{v,j}$  = mass of contaminant per unit volume of soil gas in soil type  $j$
- $C_{v,j}$  =  $H C_{w,j}$  (Henry's Law)
- $f_j$  = fraction of the treatment volume occupied by soil type  $j$  (NOTE:  $f_m + f_i = 1$ )

- $\phi_j$  = porosity of the soil in region j  
 $S_j$  = water saturation in region j  
 $\rho_{s,j}$  = density of the solid matrix in region j

$$R_j = 1 + \frac{S_j \phi_j + \rho_{s,j} K_{d,j} (1 - \phi_j)}{H(1 - S_j) \phi_j} \quad (\text{F-2})$$

$R_j$  is the retardation factor for contaminant transport in the vapor phase and is analogous to the well-known retardation factor for contaminant transport in the liquid phase.  $H$  is the dimensionless Henry's constant for the contaminant under investigation at the soil temperature.  $K_{d,j}$  is the distribution coefficient of contaminants between the solid and liquid phases. These parameters are described in more detail in Chapter 3 of the Manual. This formulation assumes a NAPL is not present and surfaces of the soil grains are completely wetted by the pore water.

Removal of contaminants from the specified volume  $V$  during SVE or bioventing occurs by two major mechanisms. The first is by extracting the soil gases from the mobile regions and the second is degradation of the contaminants. In addition, as the concentration is reduced in the mobile region, contaminants diffuse from the immobile region into the mobile region. From a simple mass balance, the change in mass in the mobile fraction of the volume by these three mechanisms is described by:

$$\frac{dm_m}{dt} = -Q C_{v,m} - \gamma_m C_{w,m} S_m \phi_m f_m V + \alpha \phi_i (1 - S_i) f_i V (C_{v,i} - C_{v,m}) \quad (\text{F-3})$$

In the immobile region, the change in mass is governed by:

$$\frac{dm_i}{dt} = -\gamma_i C_{w,i} S_i \phi_i f_i V - \alpha \phi_i (1 - S_i) f_i V (C_{v,i} - C_{v,m}) \quad (\text{F-4})$$

where:

- $Q$  = volumetric extraction rate of soil gases  
 $t$  = time  
 $\gamma_j$  = degradation decay constant in region j  
 $\alpha$  = first order mass transfer coefficient between the mobile and immobile regions

The first term in equation (F-3) represents the removal by pumping and the second term accounts for in situ degradation. The degradation is assumed to occur in the aqueous phase only. The third term accounts for mass transfer from the immobile regions into the mobile regions. The first term in equation (F-4) represents degradation in the pore water of the immobile region. The second term couples the transfer from the immobile region to the contaminant concentration in the mobile region. The transfer occurs only by diffusion in the vapor phase in this derivation, although equation (F-4) can be formulated to include liquid diffusion and advection if the water saturation is high in the immobile region.

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Equations describing the vapor concentrations in the mobile and immobile soils can be determined by substituting Equation (F-1) into (F-3) and (F-4):

$$R_m \frac{dC_{v,m}}{dt} = -\frac{Q}{\phi_m (1-S_m) f_m V} C_{v,m} - \frac{\gamma_m S_m}{(1-S_m)H} C_{v,m} + \frac{\phi_i (1-S_i) f_i}{\phi_m (1-S_m) f_m} \alpha (C_{v,i} - C_{v,m}) \quad (F-5)$$

$$R_i \frac{dC_{v,i}}{dt} = -\frac{\gamma_i S_i}{(1-S_i)H} C_{v,i} - \alpha (C_{v,i} - C_{v,m}) \quad (F-6)$$

The initial decay rate shown in the example of Figure F-1, can be estimated from equation (F-5) and (F-6) can be used to estimate the "asymptotic" decay toward zero. During the initial extraction period, mass transfer from the immobile zone plays a small role and degradation generally takes much longer. Therefore, for the initial decay in concentration, equation (F-5) may be simplified:

$$R_m \frac{dC_{v,m}}{dt} = -\frac{Q}{\phi_m (1-S_m) f_m V} C_{v,m} \quad (F-7)$$

If the average initial concentration in the contaminated volume is designated as  $C_{m,0}$ , equation (F-7) may be solved to find,

$$C_{v,m} = C_{m,0} \exp\left(-\frac{Qt}{R_m V_m}\right) \quad (F-8)$$

where  $V_m [= \phi_m (1-S_m) f_m V]$  is the air-filled pore volume within the mobile fraction of the total contaminated volume. By fitting equation (F-8) to the initial observed decay in vapor concentration, an approximation for the mobile volume is obtained if the retardation coefficient is estimated from equation (F-2). This volumetric parameter will be employed in the evaluation of rebound data. Rearranging (F-8) and utilizing the initial condition yields,

$$\frac{Q}{R_m V_m} = \frac{1}{t_{\text{measure}}} \ln\left(\frac{C_{m,0}}{C_{m,\text{measure}}}\right) \quad (F-9)$$

where the subscript measure designates a time and concentration measurement before the mobile region has been fully swept. If the air-filled volume in the mobile zone can be estimated independently (e.g., from vapor monitoring wells and boring logs), then the time required for the initial flush of the mobile region by SVE can be determined from,

$$t_{\text{flush}} \approx \frac{R_m V_m}{Q} \ln(10) = \frac{2.3 R_m V_m}{Q} \quad (F-10)$$

where the factor of  $\ln(10)$  represents a decrease in concentration by one order of magnitude. After the initial flush of the mobile zone, the extracted concentration is determined primarily by the transport of contaminants from the immobile soil and the extraction rate. To simplify the discussion, assume degradation in the immobile soils is negligible. If we assume extraction from the mobile soils continues and that the extraction rate is sufficient to maintain the vapor concentration in the mobile zone much less than the concentration in the immobile soils, mass transfer from the immobile to the mobile soils can be estimated by:

$$R_i \frac{dC_{v,i}}{dt} = -\alpha C_{v,i} \quad (\text{F-11})$$

If the average initial concentration in the contaminated volume is designated as  $C_{i,0}$ , equation (F-11) may be solved to find an estimate for the average concentration in the immobile soil,

$$C_{v,i} = C_{i,0} \exp\left(-\frac{\alpha t}{R_i}\right) \quad (\text{F-12})$$

An expression for the vapor concentration in the mobile zone during the late period of soil vapor extraction can be estimated by substituting equation (F-12) into (F-5), again neglecting degradation for brevity of discussion,

$$R_m \frac{dC_{v,m}}{dt} + \frac{Q}{V_m} C_{v,m} = \frac{V_i}{V_m} \alpha C_{i,0} \exp\left(-\frac{\alpha}{R_i} t\right) \quad (\text{F-13})$$

The solution to this equation subject to an initial condition of  $C_{v,m}=0$  at  $t=0$  is,

$$C_{v,m} = C_{i,0} \frac{\alpha V_i}{R_m V_m} \left[ \frac{Q}{R_m V_m} - \frac{\alpha}{R_i} \right]^{-1} \left[ \exp\left(-\frac{\alpha t}{R_i}\right) - \exp\left(-\frac{Qt}{R_m V_m}\right) \right] \quad (\text{F-14})$$

The initial condition of zero for the mobile soil zone is valid at late times because the initial contamination in this region has been swept away. The volume parameter for the mobile region,  $V_m$ , is determined from the initial period of extraction as described previously and the volume parameter for the immobile region,  $V_i$ , can be estimated from soil properties and the expression:

$$V_i = \phi_i (1 - S_i) (1 - f_m) V = V_m \frac{\phi_i (1 - S_i) (1 - f_m)}{\phi_m (1 - S_m) f_m} \quad (\text{F-15})$$

If the retardation coefficients can be estimated, the only remaining unknown in (F-14) is the mass transfer coefficient,  $\alpha$ . Therefore, fitting (F-14) to later extracted concentration data yields an estimate for the mass transfer coefficient. The mass transfer coefficient determines the rate of rebound and hence the anticipated dormancy period and the vapor sampling frequency to assess the vapor concentration in

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the low permeability regions. Setting  $Q=0$  in (F-14) yields an estimate for the rebound in concentration in the mobile region,

$$C_{v,m} = C_{i,0} \frac{R_i V_i}{V_m} \left[ 1 - \exp\left(-\frac{\alpha t}{R_i}\right) \right] \quad (\text{F-16})$$

The characteristic timescale for the rebound concentration in the mobile soils to increase by one order of magnitude can be estimated by,

$$t_{\text{rebound}} \approx \frac{R_i}{\alpha} \ln(10) = \frac{2.3 R_i}{\alpha} \quad (\text{F-17})$$

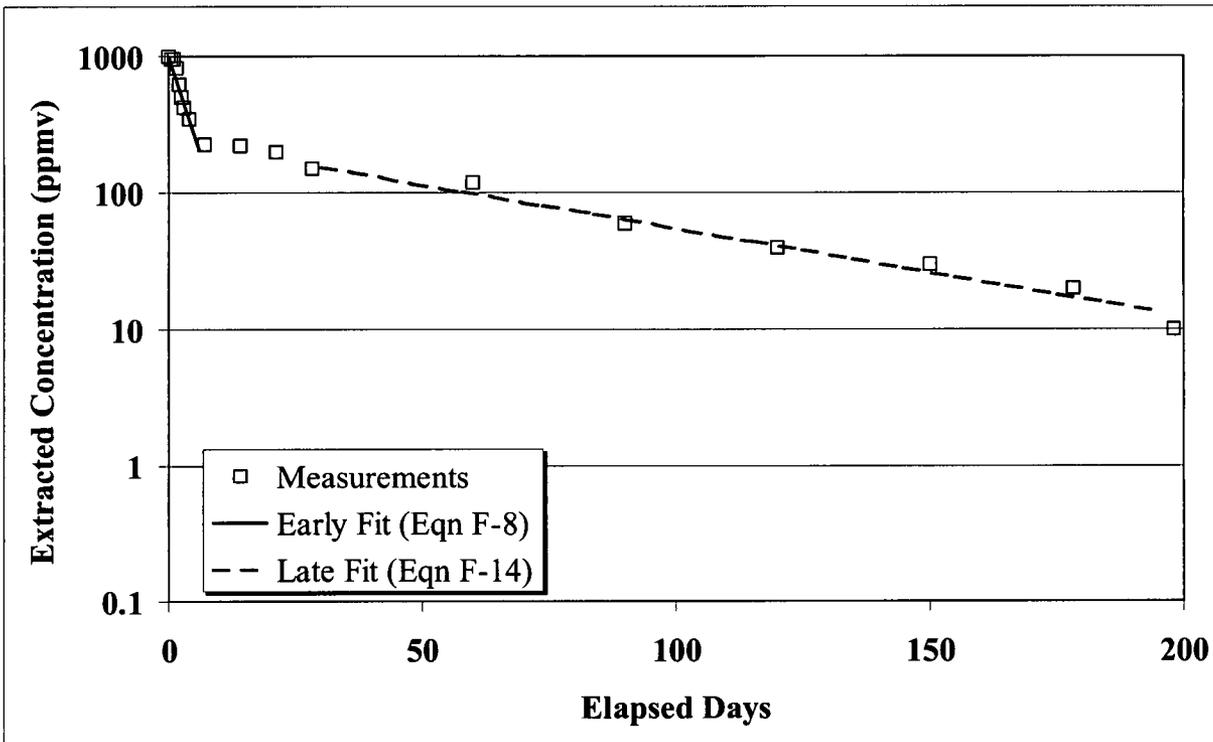


Figure F-2 Approximate equation fits to the example concentration history during SVE

The use of equations (F-8) and (F-14) is illustrated in Figure F-2 with the example data described previously. The slope of the early fit yields,

$$\frac{Q}{R_m V_m} = 0.26 \text{ days}^{-1} \quad (\text{F-18})$$

and the mobile volume parameter can be estimated if the extraction rate and retardation factor are available. The time scale for the initial flush as calculated with (F-10) is about nine days. Utilizing result (F-18) with (F-14), the best fit to the later data in Figure F-2 was achieved with the following mass transfer parameter,

$$\frac{\alpha}{R_i} = 0.073 \text{ days}^{-1} \quad (\text{F-19})$$

Variation of this parameter corresponded to changes in the slope for the fit while the initial concentration in the immobile region was varied to move the line up and down. The timescale for the rebound concentration to approach equilibrium can be calculated with (F-17). Using (F-19) an estimate of about 30 days is obtained.

### F-3. Planning and Evaluation of Historical Data

The mathematical techniques presented in the previous section are only valid if the site is adequately characterized and the remedial system is appropriately designed. Before proceeding with a rebound test, answer the following questions:

1. Does the current site conceptual model or does existing site characterization data allow an estimate for the vadose zone heterogeneities in terms of the fraction which is mobile (e.g., sands) and the fraction which is immobile (e.g., silt or clays)? Have site-specific soil physical properties been measured?
2. Do concentrations measured in extraction wells and/or vapor monitoring points allow an estimate for the total volume of contaminated soil? Are the edges of the vapor plume defined? Is a reasonable estimate for the vertical distribution of contaminants available?
3. Has the concentration history in extraction wells exhibited a relatively rapid decay followed by a slow decay?

If the answer to (1) or (2) is generally "No" then additional investigative work may be warranted before or simultaneous with a rebound test. If the answer to (3) is "No" then it may be too early for a rebound test or the site may have additional complexities. For example, if very little decay occurs or a high concentration persists for a long period then NAPL may be present or the extraction wells may not be within the original source area. The impact of NAPL existence is to add another mass term to (F-1) and additional mass transfer terms to equations (F-3) and (F-4). As a result, the extraction well concentration would persist at a higher concentration than described previously and the decay would be much slower. If these types of complexities are suspected but not identified, then further investigative work should be undertaken prior to a rebound test. Methods of investigation are described in Chapter 3 of the manual. If the answers to all three are generally "Yes" then it is probably time for a rebound test.

Planning for a rebound test starts with an evaluation of historical data. The data of most interest are the extraction rates and the concentration histories at extraction wells. If these data are available, then estimates for the rebound period and vapor sampling frequency can be determined using the techniques described in the previous section. The steps are summarized below:

1. Plot the concentration on a log scale versus time
2. Fit a line through the initial decay using equation (F-8). The slope corresponds to  $Q/R_m/V_m$  while the line is moved up and down by varying  $C_{m,0}$ .
1. Fit a curve through the later slow decay using equation (F-14) and the fitted parameter  $Q/R_m/V_m$ . The general trend corresponds to  $/R_i$  while the curve is moved up and down by varying  $C_{i,0}$ .
4. Estimate the minimum rebound period using equation (F-17).
5. Specify vapor sampling times by plotting the anticipated concentration rebound using equation (F-16). A vapor sample collected about halfway between the final extracted concentration and the equilibrium rebound concentration is highly desirable to validate the fitted mass transfer parameter  $/R_i$ . This validation will provide strong evidence for an understanding of the site during the preparation of the closure report.

After evaluating the historical data and estimating time scales, a Work Plan should be prepared for the performance of the rebound test. A well thought out and well written Work Plan as described in Paragraph 4-4 of the Manual is a key element in the success of the test. Just as important is the communication of the Work Plan to field personnel.

The first step in preparing the Work Plan is to set objectives. For rebound testing, the primary objectives are to measure the residual vapor concentrations in low permeability soils and to identify locations with high residual concentrations. With these data and estimates for the contaminated volume, the total residual mass in the site subsurface can be evaluated. If the residual mass is relatively low the site can be closed. If cleanup goals have not been met then future system operation can be optimized to meet the goals.

The following list of tasks summarizes the planning stage of a rebound test:

1. Compile historical data
  - a. Extraction rate history
  - b. Extracted vapor concentration history
  - c. Monitoring point vapor concentration history
2. Evaluate characterization and historical data
  - a. Is the site sufficiently characterized to estimate the degree of heterogeneity and the contaminated volume?
  - b. Estimate representative contaminated volume
  - c. Estimate overall mass transfer coefficient
  - d. Is a rebound test useful at this point? Is the extracted concentration low and slowly decaying?
3. Set objectives for the effort
  - a. Estimate residual mass
  - b. Locate residual mass
  - c. Estimate duration of operation to meet cleanup goals (or provide data for risk assessment modeling to close the site)
4. Specify parameters for measurement and sampling frequencies
  - a. Vapor concentrations in extraction wells prior to the start of the rebound test
  - b. Vapor concentration decay in extraction wells
  - c. Extraction rates
5. Prepare the Work Plan

#### **F-4. Field Procedures**

The execution of a rebound test occurs in three phases: (1) steady operation and monitoring of the SVE system, (2) shutdown for a period of dormancy, and (3) re-start of the SVE system. The extraction period leading up to the rebound test should be performed with as few disruptions as possible. At sites with multiple extraction wells, different extraction strategies are often employed to maximize contaminant recovery and to avoid stagnation zones. In the period leading up to the rebound test, a single extraction configuration should be employed to avoid complexities in the data interpretation.

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Several rounds of vapor sampling should be performed at normal intervals (e.g., monthly) to define the slow decay in the existing extraction configuration.

After several rounds of sampling yield consistent decay curves, the rebound test may be initiated. This phase begins by collecting a final round of vapor samples along with measurements of total concentration using field portable instruments such as a PID or FID, as appropriate. After collecting the samples and measurements, the extraction wells are closed and the extraction pumps are turned off. Care should be taken to minimize the flow of atmospheric air through the wells and into the subsurface. All extraction wells and monitoring points should be capped. The site should then be left undisturbed except for vapor sampling as specified in the Work Plan. Vapor sampling during the dormant period is best performed with a small sampling pump, if possible. The well being sampled should be purged by extracting a volume equivalent to at least three volumes of the well casing and screen. In addition, a field portable PID or FID should be used to monitor the extracted vapors to ensure a relatively steady concentration has been reached before the vapor sample for detailed analysis is collected. If the vapor sampling during the dormant period yields a clear trend to an equilibrium concentration, the system may be re-started. In past practice it was common to allow the rebound period to be "long" to ensure the site re-equilibrated before re-starting extraction. No samples were collected during the rebound period since the only parameter of interest was the equilibrated concentration. However, without sampling during the rebound period, no data will exist to demonstrate re-equilibration and a valuable assessment of the mass transfer rate between mobile and immobile soils is lost.

The final period of the rebound test is the system re-start. Just prior to starting the extraction system, a round of vapor sampling should be performed to define the endpoint of the rebound. The re-start of extraction should be in the same configuration and at the same rates as the steady period leading up to the rebound period. With the same configuration, the extraction well vapor concentrations before and after the rebound period are directly comparable. Vapor sampling during the period immediately following the re-start is critical. The maximum rebound concentration may or may not appear at the extraction wells immediately after re-start. Recall the previous discussion on the distribution of contaminants. If the extraction wells are not located in the middle of the contaminant mass, the concentration may rise for a short period before the decay associated with the sweep of the mobile soils begins. Therefore, the extracted vapors should be monitored with a field portable PID or FID during the initial hours of extraction. A vapor sample should be collected for analyses at or just after a peak is observed. If the initial concentration is the maximum and decay begins immediately, then the final rebound sample is representative of the initial extracted concentration. The goal of the vapor sampling during the re-start is to define the decay trend associated with the sweep of the mobile soils and the subsequent slower decay as the removal becomes diffusion limited. It is expected that the diffusion-limited trend will return to the decay rate observed just before the rebound period.

#### **F-5. Data Evaluation**

As described in Section F-2, analyses of the early and late concentration trends can yield estimates for the total contaminated volume and the field mass transfer coefficient. However, the objectives of a rebound test are to assess the mass of residual contamination and concentrations within low permeability materials. This section presents mathematical relationships to estimate the residual contaminant mass at a site using the data from a rebound test. Measures of vapor concentrations in the low permeability soils come directly from the rebound data. The mathematical analysis assumes the following data are available after following the field procedures described in the previous section,

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1. Analyses of extracted vapors defining the decay trend prior to the initiation of the rebound test and the extraction rate during this period;
2. Measures of mobile soil concentrations during rebound up to equilibrium with the immobile soils; and
3. Analyses of extracted vapors defining the decay trend during extraction after the rebound test and the extraction rate.

Equations describing volume-averaged vapor concentrations in the mobile and immobile soils were presented in Section F-2 as equations (F-5) and (F-6). These equations were simplified under various assumptions to yield straightforward relationships for evaluating trends in the extracted concentration. However, the equation pair can be solved exactly given an initial concentration in each soil region. Equations (F-5) and (F-6) represent coupled, first-order, ordinary differential equations for the vapor concentrations. If the extraction rate  $Q$  and the mass transfer coefficient  $\alpha$  are constant, coefficients in both equations are constant and the solution is easy to obtain. If the extraction rate varies, such as the dormancy period during rebound, then the equations can be solved piecewise using the volume-averaged concentration in each region at the end of a constant extraction rate period as the initial condition for the next constant extraction rate period. Solving the equations in terms of the vapor concentrations and designating the initial average vapor contaminant concentration in each region as  $C_{m,0}$  and  $C_{i,0}$  at some initial time  $t_0$  yields:

$$C_{v,m} = \Omega_1 \exp[ r_1 (t - t_0) ] + \Omega_2 \exp[ r_2 (t - t_0) ] \quad (F-20)$$

$$C_{v,i} = \Omega_1 \omega_1 \exp[ r_1 (t - t_0) ] + \Omega_2 \omega_2 \exp[ r_2 (t - t_0) ] \quad (F-21)$$

where:

$$\Omega_1 = \frac{C_{i,0} - \omega_2 C_{m,0}}{\omega_1 - \omega_2}$$

$$\Omega_2 = \frac{\omega_1 C_{m,0} - C_{i,0}}{\omega_1 - \omega_2}$$

$$\omega_1 = \frac{R_m r_1 + \Theta + \alpha \Phi}{\alpha \Phi}$$

$$\omega_2 = \frac{R_m r_2 + \Theta + \alpha \Phi}{\alpha \Phi}$$

$$\Theta = \frac{Q}{V_m} + \frac{\gamma_m S_m}{H(1 - S_m)}$$

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$$\Phi = \frac{V_i}{V_m} = \frac{(1-f_m)\phi_i(1-S_i)V}{f_m\phi_m(1-S_m)V}$$

$$\Gamma = \frac{\gamma_i S_i}{H(1-S_i)}$$

$$r_1 = \frac{-b + \sqrt{b^2 - 4R_m R_i [\Gamma(\Theta + \Phi\alpha) + \Theta\alpha]}}{2R_m R_i}$$

$$r_2 = \frac{-b - \sqrt{b^2 - 4R_m R_i [\Gamma(\Theta + \Phi\alpha) + \Theta\alpha]}}{2R_m R_i}$$

$$b = R_m(\alpha + \Gamma) + R_i(\Theta + \Phi\alpha)$$

Equations (F-20) and (F-21) are simple to use for matching contaminant extraction concentrations for a given extraction history. Early data may not fit well because the initial distribution of contaminants at field sites is generally very different than the uniform, average concentration assumed by the theoretical formulation. However, after the initial sweep of the mobile soils, the concentration history is generally well-behaved and approaches an average concentration because of mechanical dispersion (i.e., advective mixing). The equations provide an accurate engineering model for predicting site behavior in the later mass-transfer-limited phase if complicating factors do not exist (e.g., NAPL).

Because of the volume averaging over each soil region, very few parameters appear in the equations relative to the input required for detailed numerical modeling of an SVE system. The input and/or fitting variables are,

|   |                                   |
|---|-----------------------------------|
| Soil Physical Properties:                 | $\phi_m, \phi_i, S_m, S_i$        |
| Site-Specific Contaminant Properties:     | $H, R_m, R_i, \gamma_m, \gamma_i$ |
| Initial Vapor Concentrations:             | $C_{m,0}, C_{i,0}$                |
| Representative Contaminated Volume:       | $V$ (or $V_m$ )                   |
| Fraction of Soil Characterized as Mobile: | $f_m$                             |
| Field-Scale Mass Transfer Coefficient:    | $\alpha$                          |

This list of variables is very similar to the parameters used in two-region modeling of solute transport in saturated systems (Griffioen et al., 1998). Average soil physical properties in each region such as porosity and water saturation are usually available from independent measurements. With these soil physical properties and Henry's constant for the contaminant, the retardation coefficient in each region can be estimated as described in Chapter 2. If degradation of the contaminant is considered significant, the degradation coefficient could be estimated from the appearance of daughter compounds in the extracted vapors; however, such an analysis is beyond the scope of this document. By definition the concentration in extracted vapors is equal to the concentration in the mobile soils. Therefore, the measured extraction concentration at a specified start time  $t_0$  is the initial concentration in the mobile

region. Fitting SVE and rebound concentration data generally requires varying only four parameters in equation (F-20):  $C_{i,0}$ ,  $V$ ,  $f_m$  and  $\alpha$ . Case studies of site-specific parameter fitting are presented in the next section.

After fitting equation (F-20) to a series of extraction well concentrations associated with a rebound test, values for the fitted parameters can be checked for consistency with other existing data. Vapor concentrations are often measured in monitoring points constructed in the vadose zone around extraction wells. The monitoring points are frequently installed in low permeability soils which correspond to the immobile soil region. These measured concentrations at the start of a rebound period should correspond roughly to the fitted average initial concentration in the immobile region. Data from a number of monitoring points can be used to calculate an order-of-magnitude estimate for the total contaminated volume. This volume can be compared with the fitted representative volume. A review of boring logs or vertical flow profiles from PneuLog<sup>®</sup> can also yield an estimate for the fraction of soil which is mobile. For example, a site with distinct sand and silt intervals would only require an estimate for the total thickness of sand divided by the total thickness of the vadose zone to arrive at an estimated mobile fraction in the soil for comparison with the fitted fraction. Finally, the mass transfer coefficient can be estimated from vaporous diffusion theory in a slab. Again, a review of well logs may reveal an average thickness for immobile soil regions (e.g., thin clays or thick moist silts interbedded in sands) and previous measurements may yield the water saturation. Looking at the leading term in the linear diffusion solution leads to the following estimate for the mass transfer coefficient,

$$\alpha \approx \frac{D \phi_i^{4/3} (1 - S_i)^{10/3} \pi^2}{R_i a^2} \quad (\text{F-22})$$

where  $D$  is the vapor phase diffusion coefficient of the contaminant in free air and  $a$  is the half-length over which diffusion occurs (i.e., half the thickness of typical immobile region intervals). The fitted and calculated mass transfer coefficients should be of the same order of magnitude.

As stated above, one of the goals of the rebound test is to evaluate the mass of contaminant remaining in the subsurface. After fitting the model above to the concentrations observed with the rebound test, equation (F-1) can be used to generate an order-of-magnitude estimate for the total residual contaminant mass,

$$m_{\text{total}} = m_m + m_i = C_{v,m} R_m \phi_m (1 - S_m) f_m V + C_{v,i} R_i \phi_i (1 - S_i) (1 - f_m) V \quad (\text{F-23})$$

If the field conditions are adequately modeled by the two-region concept and the fitted parameters are consistent with other information, then the model of the rebound data yields powerful information regarding closure or optimization of the existing system. For example, the calculations may yield estimates for a small residual mass and/or the attainment of cleanup goals. For optimization, the model can predict durations of extraction to reach cleanup goals for various extraction rates.

## F-6. Case Studies

This section presents two case studies for the evaluation of SVE and rebound concentration data using the mathematical models described in this appendix. Both sites are located in California's Central

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Valley and both were contaminated with TCE and PCE. The first example is a relatively simple site where two extraction wells were operated simultaneously for nearly two years at a steady flow rate with a number of shutdown periods. Vapor sampling was performed only with the combined flow. Individual wells were not sampled. The second example is from a more complicated site where from one to four wells were operated simultaneously in various configurations with varying extraction rates and two rebound tests over a five year period. Modeling of this more complicated site required a detailed review of extraction rates, durations, and measured concentrations from both individual wells and the combined flow in the manifold.

*a. Case Study Site 1*

Historical operation of SVE at Site 1 was simultaneous extraction from two wells without any flow balancing (i.e., the same vacuum was applied to both wells). In addition, only total flow was measured and all extracted concentrations were collected from the combined vapor stream. Therefore, historical data do not exist for the concentrations and masses removed from individual wells. The historical TCE concentrations measured in the combined stream during the first year and half of SVE at Site 1 are illustrated in Figure F-3. Startup of the system involved a couple of brief shutdowns and a long shutdown occurred after the first month. The system was re-started during the ninth month. The extraction history used to model the process consisted of 69 constant flow segments but these were generally either 400 cubic feet per minute or zero. The extraction rates, start times and stop times were estimated from monthly status reports. The assumed soil properties for the modeling are listed in Table F-1.  $K_d$  was set equal to one because organic carbon was not detected in any soil samples from the site.

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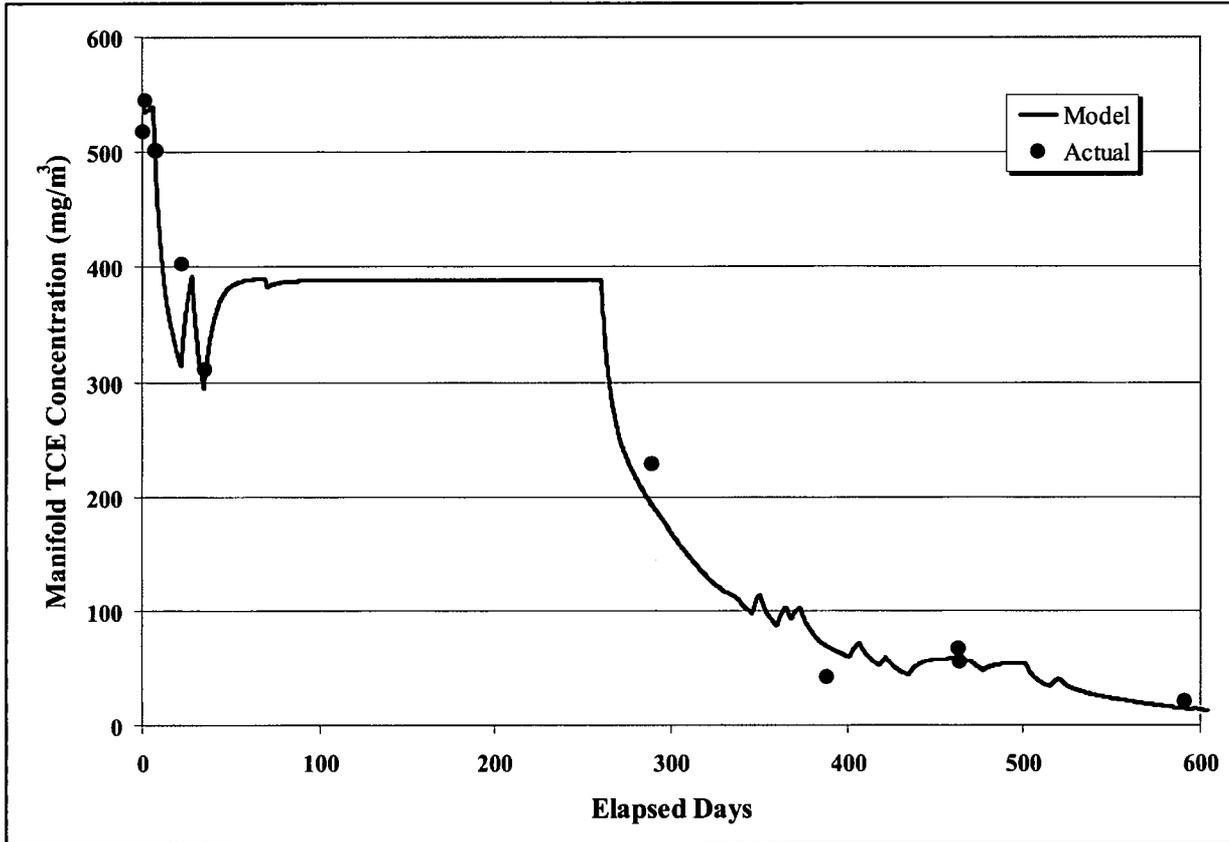


Figure F-3 Summary of historical TCE concentration measurements

| <b>Table F-1.</b>   |                          |                    |                      |
|---|--------------------------|--------------------|----------------------|
| <b>Input Parameters Yielding the Best Fit of the SVE System Manifold Concentrations</b> |                          |                    |                      |
| <b>Soil Property</b>  | <b>Units<sup>a</sup></b> | <b>Mobile Zone</b> | <b>Immobile Zone</b> |
| Initial Vapor Concentration   | mg/m <sup>3</sup>        | 545                | 545                  |
| Porosity  | ND                       | 0.487              | 0.487                |
| Water Saturation  | ND                       | 0.25               | 0.40                 |
| Grain Density   | kg/m <sup>3</sup>        | 2.66               | 2.66                 |
| Characteristic Thickness  | m                        | -                  | 0.4                  |
| Characteristic Volume   | m <sup>3</sup>           | 288,100            | 864,200              |
| K <sub>d</sub>  | L/kg                     | 0                  | 0                    |
| Degradation Rate  | 1/yr                     | 0                  | 0                    |
| <b>TCE Properties</b>   |                          |                    |                      |
| Henry's Constant  | ND                       | 0.38               |                      |
| Octanol-Water Partition   | ND                       | 200                |                      |
| Diffusion Coefficient in Air  | m <sup>2</sup> /day      | 0.68               |                      |

<sup>a</sup>ND = dimensionless

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The two-region model provided a good match to the historical manifold TCE concentration. As described in Section F-5, the model was run varying the initial soil vapor concentration, the total contaminated volume, the percentage of the subsurface categorized as mobile, and the mass transfer coefficient between mobile and immobile zones. The best-fit values are listed in Table F-1. The total characteristic volume was estimated to be 40,690,000 cubic feet (1,152,300 cubic meters). Of this total volume, 25% was represented as mobile and 75% as immobile. For a vadose zone thickness of 80 feet (24.4 m), the characteristic radius was 400 feet (123 m) equivalent to a surface area of about 12 acres. This total characteristic volume was consistent with the flow observations from PneuLog<sup>®</sup> and the vacuum responses at monitoring points. The two wells influenced a very large area because they intersected a permeable sand channel near the bottom of the vadose zone. In addition, usage history indicated a number of possible release points for contaminants existed across the site. Using the initial estimated vapor concentration of 545 mg/m<sup>3</sup>, the best-fit total volume yields an estimated total original mass for TCE of 1,074 pounds (487 kg). The overall mass transfer coefficient between the mobile and immobile soils was estimated to be 0.108 day<sup>-1</sup> corresponding to a time scale of 9 days. This suggests rebound during shutdown periods was relatively rapid.

The calibrated two-region model developed by matching the historical data for the combined extraction was used to forecast future performance. Model predictions for the combined concentration and cumulative mass removed are presented in Figure F-4. The model forecasts reaching an equivalent TCE concentration of MCL in the pore water of the immobile soils around day 800.

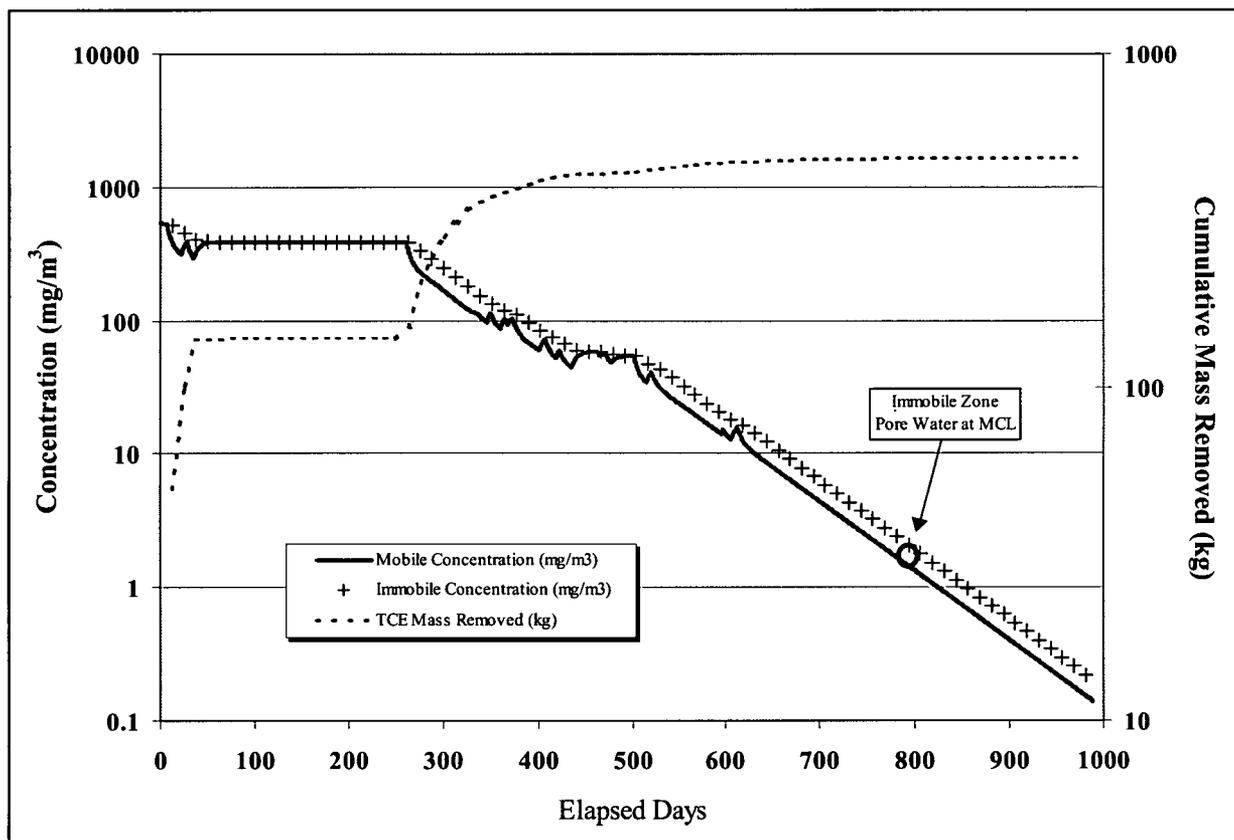


Figure F-4 Forecast for continued operation of the existing SVE system

*b. Case Study Site 2*

Site 2 is located in the Central Valley of California. The subsurface at Site 2 readily meets the conceptual model of mobile and immobile zones for air movement during SVE. PneuLog<sup>®</sup> flow profiles revealed only about 20 % of the vadose zone allowed effective air flow. These mobile zones consisted of interbedded sand layers within an immobile zone predominantly made up of moist silts and fine sands. Historical concentration and flow data were available from both the manifold (representing the cumulative extraction rate from all wells and the mixed contaminant concentrations), individual extraction wells, and vapor monitoring wells. The history shows the concentrations rising during the first week of operation. After this initial period, both the TCE and PCE concentrations exhibited the classic exponential decay. The initial 90 days of extraction were performed with a single extraction well (VW-01) near the center of the suspected source area. This 90-day period was followed by additions and modifications to the extraction configuration using three other surrounding wells and two rebound periods.

The two-region model was applied using soil properties measured at the site and a detailed extraction history employing 193 constant flow segments over a four-year period to fit the observed PCE concentrations in the manifold and from well VW-01. The procedure followed to fit the data is outlined in Section F-5. The resulting model fits are illustrated in Figures F-5 and F-6. Similar results were achieved for TCE data. The initial concentration in the mobile phase was assumed equal to the early (day 9) peak concentration observed in the manifold. The other best-fit values for PCE are listed in Table F-3. The total characteristic volume of contaminated soil was estimated to be 1,099,400 cubic yards (840,600 m<sup>3</sup>) with roughly 18 % characterized as mobile and 82 % immobile. For a depth to groundwater of 105 feet this yields an equivalent radius of 300 feet for the contamination. This radius correlated well with the overall dimensions of observed PCE contamination at the start of remediation. The characteristic diffusion length estimated for the immobile zone was about 1.15 feet (0.35 m) corresponding to an average total thickness of about 2.3 feet for each immobile zone region. This characteristic length was calculated using equation (F-22) and the fit mass transfer coefficient. In addition, this length is consistent with the observations from the PneuLog<sup>®</sup> flow profiles. The best-fit immobile zone initial vapor concentration (565 ppmv) was equivalent to the mobile zone (650 ppmv) indicating the mobile and immobile regions were in equilibrium. The values differ because differing soil properties yield differing partitioning components. Using the estimated initial mobile and immobile zone PCE vapor concentrations and the best-fit total volume yielded an estimated total initial mass for PCE of 4,130 pounds (1,873 kg).

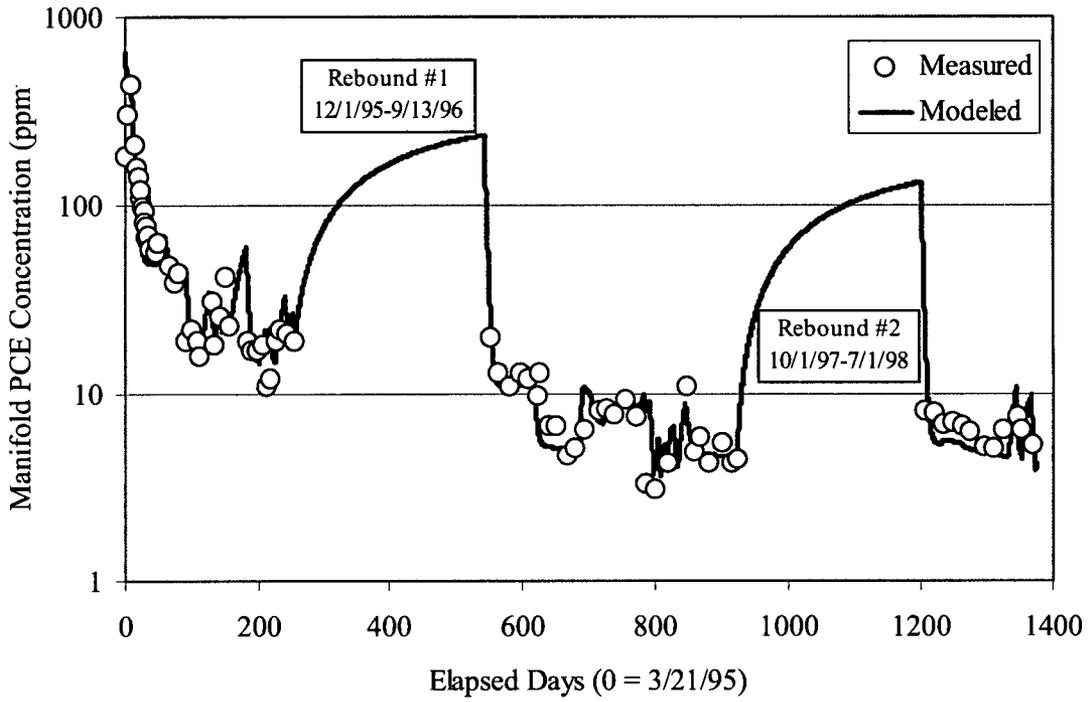


Figure F-5 Measured and modeled PCE vapor concentrations at the manifold

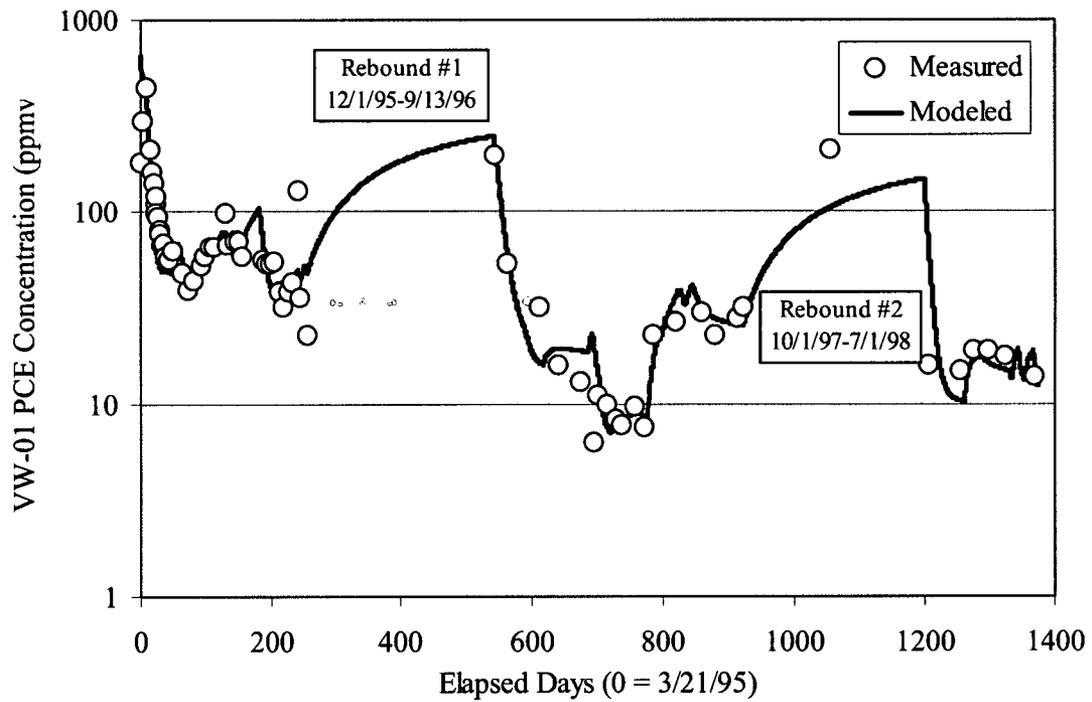


Figure F-6 Measured and modeled PCE vapor concentrations in well VW-01

| <b>Table F-2.</b>                                    |                          |                    |                      |
|--|--------------------------|--------------------|----------------------|
| <b>Parameters for Modeling PCE Removal at Site 2</b> |                          |                    |                      |
| <b>Soil Property</b>                                 | <b>Units<sup>a</sup></b> | <b>Mobile Zone</b> | <b>Immobile Zone</b> |
| Initial Vapor Concentration                          | ppmV                     | 650                | 565                  |
| Porosity   | ND                       | 0.473              | 0.507                |
| Moisture Content (vol)                               | ND                       | 0.080              | 0.343                |
| Grain Density  | g/cm <sup>3</sup>        | 2.65               | 2.65                 |
| Characteristic Thickness                             | m                        | -                  | 0.35                 |
| Characteristic Volume                                | m <sup>3</sup>           | 151,300            | 689,265              |
| K <sub>d</sub>                                       | L/kg                     | 0.018              | 0.072                |
| Degradation Rate                                     | 1/yr                     | 0                  | 0                    |
| <b>PCE Properties</b>                                |                          |                    |                      |
| Henry's Constant                                     | ND                       |                    | 1.10                 |
| Octanol-Water Partition                              | ND                       |                    | 600                  |
| Diffusion Coefficient in Air                         | m <sup>2</sup> /day      |                    | 0.63                 |

<sup>a</sup> ND = dimensionless

With a calibrated model of site behavior during SVE, forecasts of future performance were possible and residual mass and concentration estimates could be compared with cleanup goals. Predicted future performance at the site is illustrated in Figure F-7 where the operation of two wells was found to be the optimum. The forecasted, optimized operating time to reduce the average PCE vapor concentration in the immobile zone to 10 ppmv is about 28 months beyond the operations at the time of modeling. The residual PCE mass at 10 ppmv is estimated to be 61 pounds. To reach an average of 1 ppmv in the immobile zone, extraction must continue another 20 months. At this end, the residual PCE mass is estimated to be 6 pounds.

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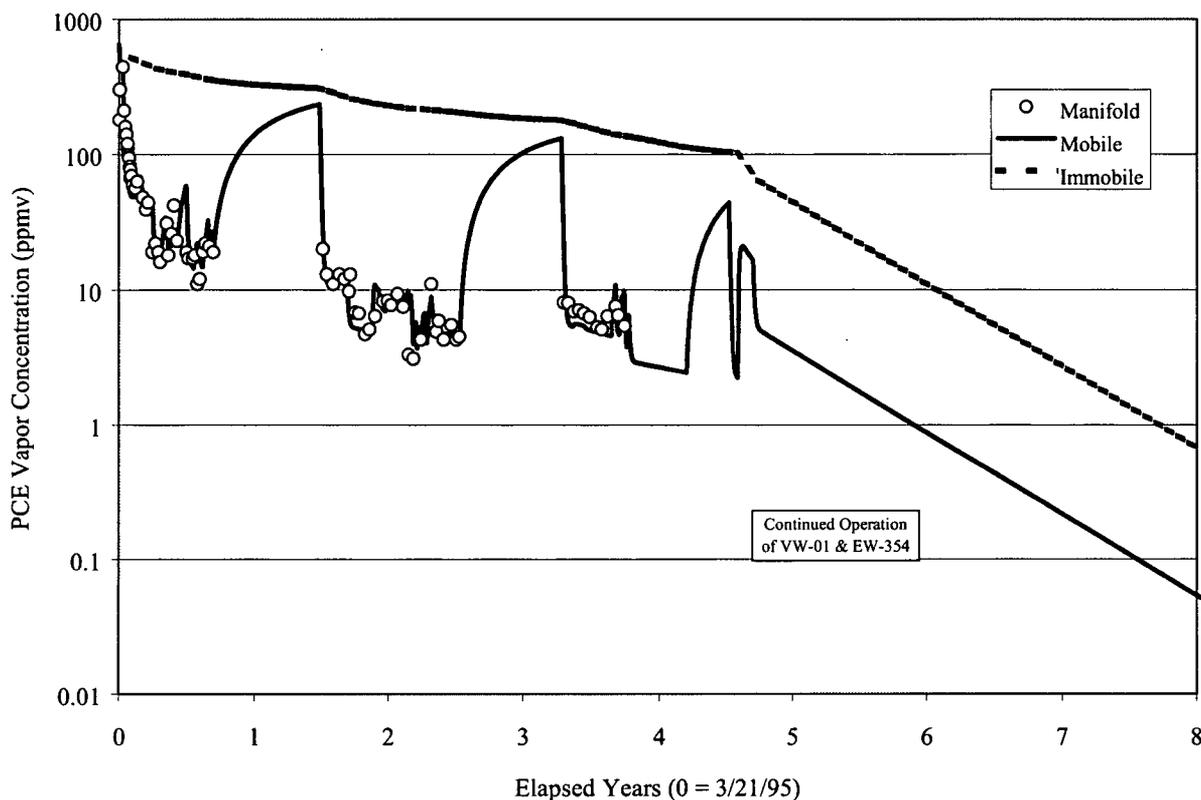


Figure F-7 Forecast for PCE removal using optimized extraction well configuration.

## F-7. References

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