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30 November 1995

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Soil Vapor Extraction and Bioventing

ENGINEER MANUAL

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

CEMP-RT

Manual
No. 1110-1-4001

30 November 1995

Engineering and Design
SOIL VAPOR EXTRACTION AND BIOVENTING

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 environmental, civil, geotechnical, chemical, mechanical, and electrical engineers; geologists, hydrogeologists, and soil scientists; chemists; project managers; and others involved in any phase of SVE and BV projects. The manual describes current best practice for SVE and BV site characterization, system design, and system start-up and operations. Both SVE and BV technologies are still developing, and updates to this manual will be issued as appropriate.

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

FOR THE COMMANDER:

ROBERT H. GRIFFIN
Colonel, Corps of Engineers
Chief of Staff

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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 environmental, civil, geotechnical, chemical, mechanical, and electrical 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 (Baker and Becker 1995).

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	Johnson et al. 1994 USEPA 1989a USEPA 1991d USEPA 1992a
Important physical, biological, and chemical parameters	ASTM D5126-90 Corey 1986a DePaoli et al. 1991c Downey and Hall 1994 Johnson, Kemblowski, and Colthart 1990b Ostendorf and Kampbell 1991 USEPA 1986 USEPA 1991c
Pilot testing and design	DePaoli et al. 1991c DiGuilio et al. 1990 Hinchee et al. 1992 Johnson et al. 1990a Johnson and Ettinger 1994 Sayles et al. 1992
Modeling	Baehr, Hoag, and Marley 1989 Becket and Huntley 1994 DePaoli et al. 1991b DePaoli et al. 1991c Falta, Pruess, and Chestnut 1993 King 1968 Marley et al. 1990a Massmann 1989 McWhorter 1990 Muskat and Botset 1931 Rathfelder, Yeh, and Mackay 1991 Shan, Falta, and Javandel 1992 USEPA 1993c Wilson, Clarke, and Clarke 1988
Equipment specification and operation	DePaoli et al. 1991b Johnson et al. 1990a USEPA 1992a USEPA 1993c
Evaluation of system performance	Buscheck and Peargin 1991 DePaoli et al. 1991b DePaoli et al. 1991c Peargin and Mohr 1994 Travis and Macinnis 1992 USEPA 1989a USEPA 1989b USEPA 1990a USEPA 1992a

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. The U.S. Environmental Protection Agency (USEPA) estimates 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) in soil constitute an ongoing source of contamination of soil gas and the lower atmosphere, primarily by volatilization and diffusion, and of groundwater, primarily by infiltration and dissolution. 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 advected in the subsurface, but treatment of contaminants takes place in situ rather than aboveground, thereby reducing remediation costs. Microorganisms in the unsaturated zone biodegrade the contaminants, in the case of aerobic mineralization, to carbon dioxide, water, and biomass. 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 semivolatile 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 lower atmosphere.

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 Petroleum Institute (Thornton and Wootan 1982; U.S. District Court 1994). In recent years, use of SVE has been extended to hazardous waste sites (Kress et al. 1992; Lewis 1993). Of the total of 666 treatment technologies that US EPA selected for Superfund remedial actions through fiscal year 1993, SVE made up 121, or 18 percent. This constituted the largest number of selections of any of the technologies that US EPA characterizes as "innovative"; moreover, when all treatment technologies, both "established" and "innovative" are considered, selections of SVE were second in frequency after solidification/stabilization (190, or 29 percent). As of September 1994, 69 of the 121 SVE projects at Superfund sites are in predesign/design; 42 have completed designs, are being installed, or are operational; and 10 are completed (USEPA 1994). In 1993, USEPA designated SVE as a presumptive remedy for CERCLA sites contaminated with VOCs (USEPA 1993d). SVE is also widely used in Europe and is considered standard procedure in Germany (Hiller 1991).

g. BV is a more recent and less commonly applied technology. Evidence of unsaturated zone biodegradation resulting from air advection was first reported by the Texas Research Institute (1980; 1984). In the late 1980s and early 1990s, the U.S. Air Force studied BV at Hill, Tyndall, and several other Air Force bases (DePaoli et al. 1991a,b,c), and in 1992 began an initiative to test BV at over 135 sites (AFCEE 1994a). Based on their results, the U.S. Air Force now regards BV as a presumptive remedy for jet fuel-contaminated sites. The use of SVE and BV is expected to increase. BV is described in some detail in this EM, but coverage defers to a BV principles and practices manual currently being prepared by the U.S. Air Force and USEPA. The use of SVE and BV is expected to increase.

1-5. Scope

This manual (Baker and Becker 1995) 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. It focuses more on design guidance than on fundamental chemical, physical, and biological processes underlying SVE and BV. It also focuses more on SVE than BV since a BV engineer manual is currently (1995) in preparation by the U.S. Air Force and USEPA.

a. SVE and BV are relatively new technologies. The basic physical principles governing SVE are fairly well understood, but details of system design are often determined empirically rather than by rigorous analysis (Massmann 1989; Johnson et al. 1990a).

b. 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. Partly because SVE and BV are young technologies, design methodology is not firmly established. The numerous site-specific conditions which come into play in any given SVE/BV situation further 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 being continually developed. Therefore, a review of the latest case studies, models, and references prior to designing an SVE/BV system is recomended.

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.

(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.

(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:

Phone number	(402) 697-2561
Fax number	(402) 697-2595

(3) Other Federal agencies and research organizations also provide BBS and electronic databases. In addition, some of the data can be obtained on floppy diskette and CD ROM formats. Tables 1-1 and 1-2 list the more popular databases, bulletin boards, and expert systems available for SVE and BV technologies.

(4) Several telephone hotlines are available as sources of information. These include the USEPA's RCRA/Superfund Hotline, 800-424-9346; and the U.S. Department of Energy's Environmental Technology Information Service, 800-845-2096.

Table 1-1
System Characteristics of Federal Databases

System Name	Technology Description	Performance Data	Cost Data	Case Studies	Updated Periodically	User Fees	Public Access	System Operator	On-Line Capability
DATABASES									
DIALOG Information Services					X	X	X	X	X
Records of Decision System	X	X	X	X	X		X	X	X
Underground Storage Tanks Case History Data Base System	X	X	X	X	X		X	X	X
Vendor Information System for Innovative Treatment Technologies (VISITT)	X	X	X		X		X	X	X
BULLETIN BOARDS									
Alternative Treatment Technology Information Center (ATTIC)	X	X	X	X	X		X	X	X
Defense Environmental Electronic Bulletin Board	X						X		X
OSWER Bulletin Board System					X		X		X
EPA-OSW "CLU-IN" BBS for Clean-Up Technologies					X		X	X	X
EPA-ORD Cincinnati BBS for Remediation Technologies	X	X		X	X		X		X

Table 1-2
Summary Table of Federal Databases (Continued)

Name	Objective	Data/Technology Information	Hardware/Software	Contacts
DIALOG Information Services	This on-line system is a bibliographic retrieval system that represents the reports of major U.S. Federal government agencies and the government agencies from many foreign countries.	NTIS includes summaries of government-sponsored research, development, and engineering reports, as well as other analyses prepared by government agencies, their contractors, and foreign governmental agencies.	DIALOG is accessible with an IBM PC or Macintosh, a modem (9600 baud), and communications software.	DIALOG Information Services 800/334-2564
Records of Decision System (RODS)	RODS contains the full text of Superfund Records of Decision for hazardous waste cleanup sites nationwide.	RODS contains the full text of Superfund Records of Decision for hazardous waste cleanup sites nationwide.	RODS is available on CD ROM through NTIS though the RODS staff can provide searches for EPA contractors and federal agencies working on Superfund projects.	POC-Jalania Ellis 703-603-8884 U.S. Environmental Protection Agency RODS Contractor Staff 703/416-0703
Underground Storage Tanks Case History File Data Base System	The database system is a compilation of factual data from site coordinators, detailing corrective action methods to guide leaking underground storage tank corrective actions.	The database includes information on technologies, selection of appropriate technology, cost, and effectiveness.	The system is accessible via a personal computer, modem, and a telecommunications software package.	Available through ATTIC hotline/SYSOP
Vendor Information System for Innovative Treatment Technologies (VISITT)	This database is a software system used by technology vendors, government, and private cleanup personnel.	The database includes a variety of information ranging from summary performance data to waste limitations.	VISITT requires an IBM or IBM compatible PC with at least 640 K RAM, DOS 3.3 or higher, and 10 megabytes of hard disk space.	U.S. Environmental Protection Agency 513-891-6561 to order, call (513) 489-8190 or Fax - 8695 or available through CLU-IN BBS VISITT HOTLINE 1-800-245-4505

Table 1-2
(Concluded)

Name	Objective	Data/Technology Information	Hardware/Software	Contacts
Alternative Treatment Technology Information Center (ATTIC)	ATTIC is a collection of hazardous waste databases that are accessed through a computer bulletin board. The bulletin board is an information retrieval network that provides up-to-date technical information on alternative treatment technologies for hazardous waste.	The bulletin board includes features such as news items, bulletins, and special interest conferences. The central component of ATTIC is the ATTIC Data Base which contains abstracts and summaries from technical documents and reports.	ATTIC contains two access mechanisms: Hotline/System Operator, and an On-Line System.	ATTIC is staffed by the Scientific Consulting Group, Inc., Rockville, MD Primary Contact: Gary Turner (System Operator) Joyce Perdek (RREL Project Manager) System Operator (703) 908-2137 Online Computer Access (703) 908-2138
Defense Environmental Network and Information Exchange (DENIX)	The bulletin board serves as a centralized communication platform for disseminating Defense Environmental Restoration Program (DERP) information pertaining to DoD's scheduled meetings, training, cleanup sites, and technologies.	The bulletin board provides user mail service, multi-user access, and upload/download features; and permits access to 800 number dial-in and to other environmental data networks.	The bulletin board can be accessed with a dumb terminal or modem emulating a VT100, (300 to 14400 baud); registration required.	U.S. Army Construction Engineering Lab (CERL) DENIX Sysop 217/373-4519 On-Line access 217/333-5067
EPA-OSW "CLU-IN" BBS for Clean-Up Technologies	The "CLU-IN" BBS is an on-line system containing bibliographic references and abstracts for literature concerning a variety of remedial technologies.	"CLU-IN" BBS provides up-to-date literature and technical reference information on a variety of remedial technologies.	"CLU-IN" BBS is accessible with a combination of a computer, a modem, and a communications software package.	U.S. Environmental Protection Agency Office of Solid Waste System Operator 301/589-8368 On-Line 301/589-8366
EPA-ORD Cincinnati BBS for Remediation Technologies	This bulletin board provides on-line retrieval of information pertaining to technical information and site data for remediation technologies.	The Cincinnati BBS offers information on technologies and site-specific performance data for remediation technologies.	The computer system required to access the Cincinnati BBS must include a personal computer, modem and a communications package.	U.S. Environmental Protection Agency Office of Research and Development System Operator Patrick Burke 513/569-7525 On-Line 513/569-7610

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 in 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 complete project team is essential. 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 sumarized 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, 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 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, cosolvation 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). Nonequilibrian effects are further discussed in paragraph 2-3*b*, and their manifestations are presented in

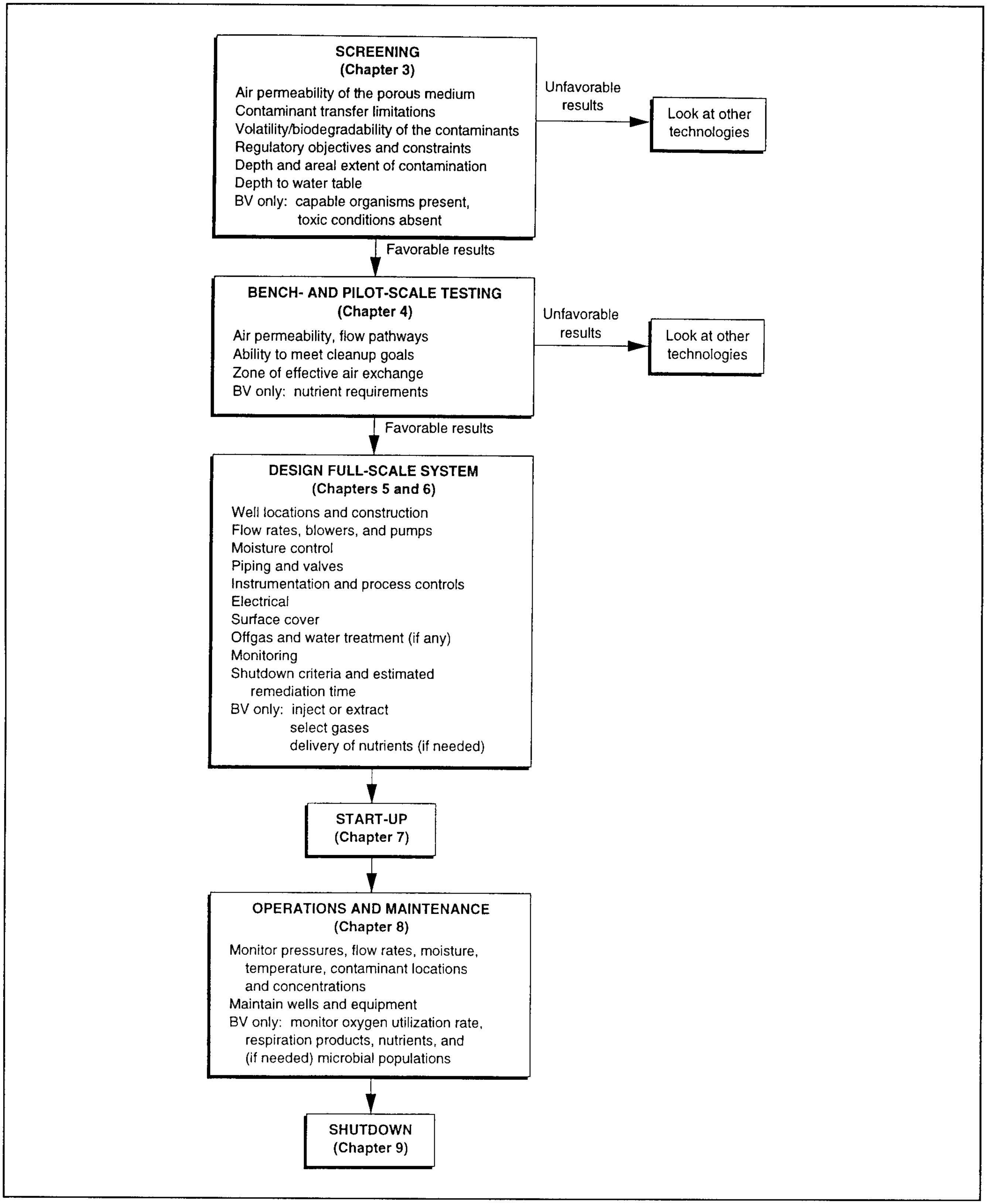
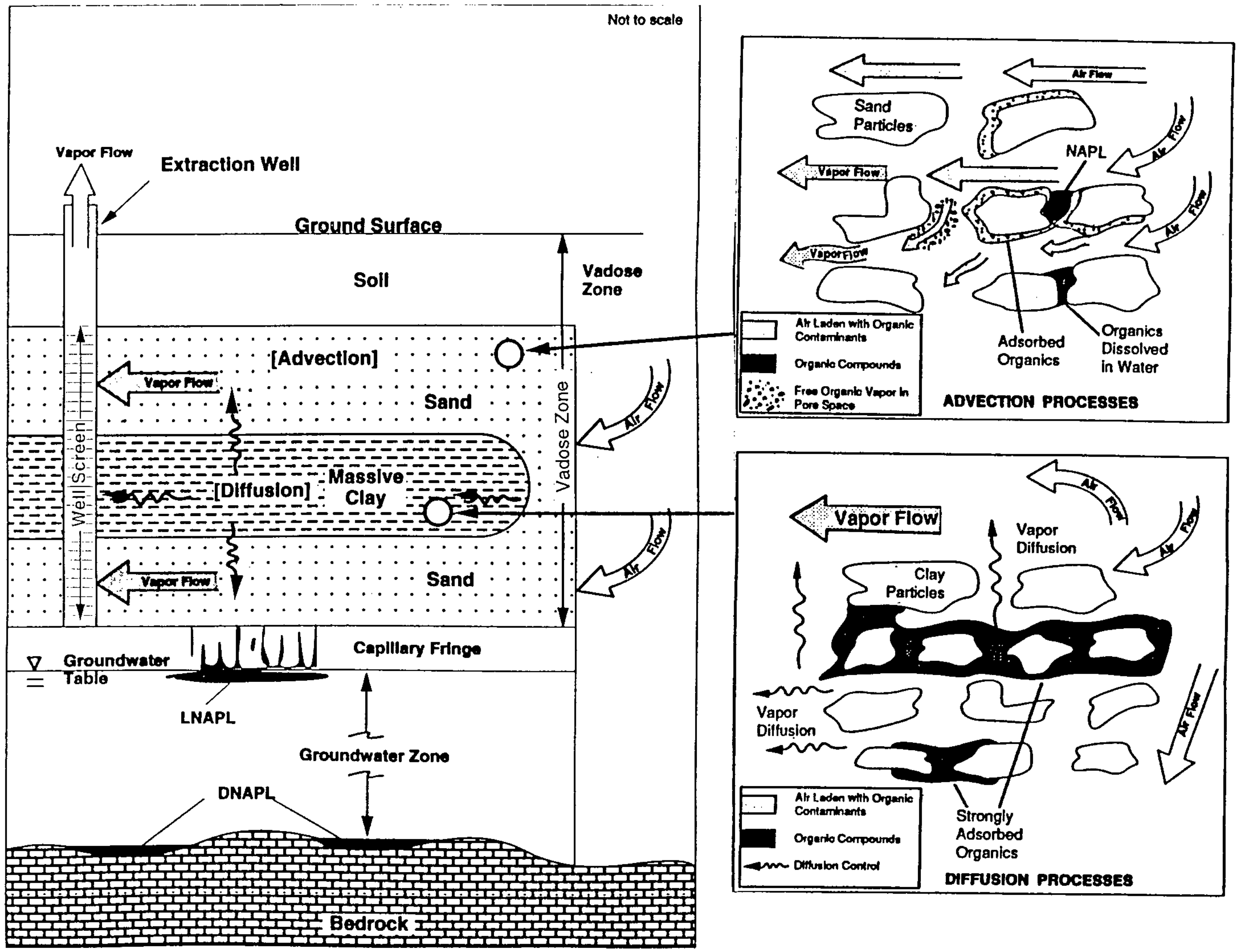


Figure 2-1. SVE/BV application strategy



Source: after USEPA 1991c

Figure 2-2. SVE transport processes

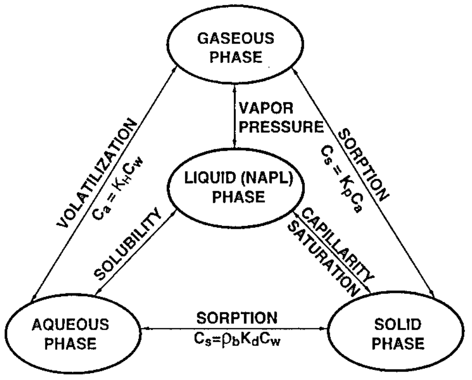
paragraph 9-9. The following paragraphs underscore the importance of recognizing and designing for nonequilibrium conditions.

(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 widespread tendency 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 weighed against the competing need to maximize the radii of pressure influence about air extraction and injection points, which generally involves maximizing venting flow rates, to find an optimal operating point. 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 paragraphs 5-2*a*, 5-3*a*, and 9-9.

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.



Where C_a, C_w, C_s = Concentration of VOC component in air, water, solid
K_H = Henry's constant
K_p = Partition coefficient
K_d = Distribution coefficient
ρ_b = Soil bulk density

after Lewis et al. 1991 and Quigley 1995

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 (g m^{-3}) with the Ideal Gas Law

$$C_v = M\,P_v\,/\,R\,T \tag{2-1}$$

with molecular weight M (g mol^{-1}), universal gas constant R (8.314 Pa m^3 mol^{-1} °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_{vj} 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 $P°_j$ of the pure constituent i (which is a function of temperature)

$$P_{vj} = X_i\,P°_j \tag{2-2}$$

(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_1 (mass/volume of liquid), at equilibrium

$$K_H = C_v/C_l \tag{2-3}$$

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^3/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 and 270 °K (0 °C) is 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 adsorption 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 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.

(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.

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) 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.

(2) Porosity (n) is the (dimensionless) ratio of the void volume to the total volume 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 ρ_b, which is the dry weight of soil per bulk volume (i.e., of both soil and pore space) by

$$n = 1 - (\rho_b / \rho_s) \tag{2-4}$$

with particle density ρ_s. For many inorganic soil particles, ρ_s is approximately equal to 2.65 g/cm^3. Air-filled porosity is designated n_a. Geotechnical engineers typically term ρ_b the dry density.

(3) Saturation S is the volume fraction or percent of a fluid per volume of soil pore space. When expressed as the volume fraction or percent of water per volume of soil pore space, it is termed "degree of water saturation," S_w (dimensionless), i.e., $S_w = V_w/V_{pores}$. 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 in a soil sample divided by its oven-dry mass, $w = M_w/M_{soil}$. When expressed on a volume basis, moisture content θ is the volume of water in a sample divided by the total bulk volume 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 ρ_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. 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).

(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_{nwo} can be defined such that $S_w + S_{nwa} + S_{nwo} = 1$.

(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

$$P_c = P_n - P_w \tag{2-5}$$

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]; ρ, density [M L^{-3}]; and g, acceleration of gravity [L T^{-2}]. Thus, dividing Equation 2-5 through by ρ and g,

$$h_c = h_n - h_w \qquad (2\text{-}6)$$

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, ψ) (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.

Table 2-1
Pressure/Pressure Head Conversions

	Units of Pressure
1 bar	= 10^5 N m^{-2}
	= 0.987 atmospheres
	= 14.5 psi
	= 10^6 dynes cm^{-2}
	= 100 kPa
	Units of Pressure Head
and is equivalent to:	1020 cm column of water 75.01 cm column of Hg

Example:

A magnehelic vacuum gauge mounted on the wellhead of a vent well reads in cm H_2O (gauge). In other words, it reads 0 cm H_2O 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_2O, which is equivalent to a vacuum head of 7.35 cm Hg.

i.e., $\dfrac{100 \text{ cm } H_2O}{1020 \text{ cm } H_2O} = \dfrac{7.35 \text{ cm Hg}}{75.01 \text{ cm Hg}} = \dfrac{9.8 \text{ kPa}}{100 \text{ kPa}}$

These can also be expressed as gauge pressure heads of 100 cm H_2O 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 75.01 cm Hg + (-7.35 cm Hg) = 67.66 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, 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 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.

(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

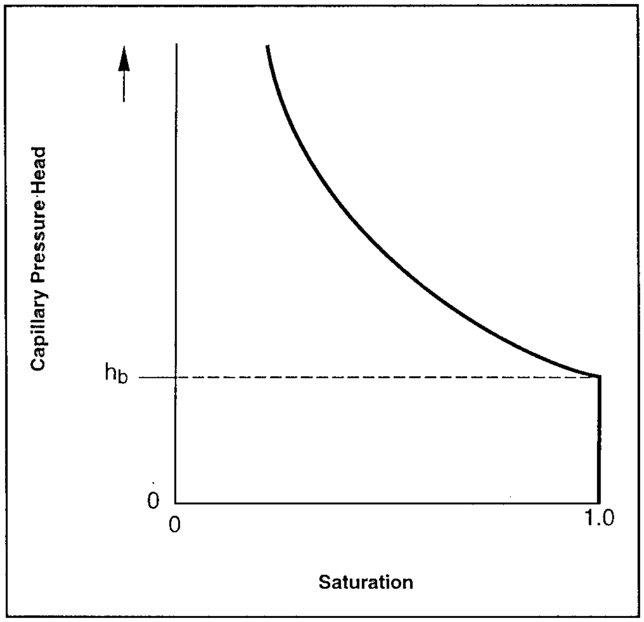


Figure 2-4. Capillary pressure head-saturation curve

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:

$$k = K_s \mu_w / \rho_w \, g \tag{2-7}$$

where μ_w is the dynamic viscosity of water [M L^{-1} T^{-1}] and ρ_w is the density of water [M L^{-3}]. For water at approximately 293 °K, k = (10^{-7}m-sec)(K_s), where k is expressed in units of m^2 and K_s in m·sec^{-1}, or k = (10^{-5} cm-sec) (K_s) where k is expressed in units of cm^2 and K_s in cm 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 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 non-linear 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.

(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

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

where

q = discharge per unit area [L/T]

k_i = intrinsic permeability [L^2]

ρ = fluid density [M/L^3]

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

μ = dynamic fluid viscosity [M/L-T]

∇ = gradient operator [L^{-1}]

H = total head [L]

(1) As described in paragraph 2-3*c*(9), intrinsic permeability k is a property of the porous medium. Density ρ and viscosity μ are properties of the particular fluid under consideration. Values of viscosity of air at normal temperature and pressure (NTP) are 1.83×10^{-5} newton·s m^{-2}, equivalent to 1.83×10^{-4} gm cm^{-1} s^{-1} and 1.83×10^{-2} centipoise. Likewise, values of density of air at NTP are 1.20×10^{-3} Mgm m^{-3}, equivalent to 1.20×10^{-3} gm cm^{-3} and 7.49×10^{-2} lb ft^{-3}. NTP is a gas industry reference, with normal temperature defined as 21.1 °C (70 °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) [$ML^{-1}T^{-2}$] and as potential ϕ (energy per unit mass) [L^2T^{-2}]. To convert head to pressure, divide head by ρg, where ρ 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 ρ (Hillel 1980a).

(3) Total fluid potential ϕ (i.e., mechanical energy per unit mass) [L^2T^{-2}] is defined as

$$\phi = gz + \frac{v^2}{2} + \int_{P_o}^{P} \frac{1}{\rho} dP \tag{2-9}$$

where

z = elevation [L]

v = fluid velocity [L/T]

P = absolute pressure [M/LT^2]

(a) The first term of Equation 2-9, known as the Bernoulli equation, 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 ϕ becomes

$$\nabla \phi = \frac{1}{\rho} \nabla P \tag{2-10}$$

and Darcy's law for vapor flow is

$$q = \frac{k_a}{\mu} \nabla P \tag{2-11}$$

(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 2-3*c*).

(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) discussed 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

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

where

n_a = air-filled porosity

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

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

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

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

(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 2-4*e*). 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

$$\nabla \cdot (k_a \nabla P^2) = 0 \qquad (2\text{-}15)$$

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

$$\nabla^2 P^2 = 0 \qquad (2\text{-}16)$$

(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 which 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 which 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

$$\frac{d^2 P^2}{dx^2} = 0 \qquad (2\text{-}17)$$

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:

$$P^2 - P_{atm}^2 = \frac{2Q_l P^* \mu}{bk_a}(L - x) \qquad (2\text{-}18)$$

where

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

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

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 $P = P_{atm}$ at $r = r_e$ is

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{\pi b k_a}\ln\left(\frac{r_e}{r}\right) \qquad (2\text{-}20)$$

where

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

r_e = radius of pressure influence [L]

(8) The radius of pressure influence (r_e) is the point at which $P = P_{atm}$. Although this parameter is required for solution of Equation 2-19, its nature is somewhat problematic. Mass balance dictates that for continuous withdrawl 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 radial flow, which indicate that r_e increases in proportion to the square root of time (McWhorter and Sunada 1977; McWhorter 1990). 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.

(9) In a theoretical sense, the foregoing discussion indicates that r_e is a mathematical artifice necessary for solution of Equation 2-19. In a practical sense, r_e is the limit of measurable pressure influence resulting from an extraction well. In either case, it is a necessary parameter for analysis of permeability test data using Equation 2-20. 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).

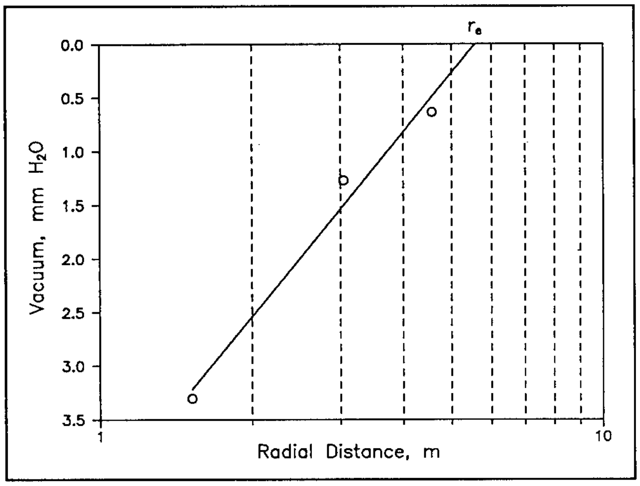


Figure 2-5. Use of distance-drawdown graphs to determine r_e

(10) 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.

(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

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

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

$$P^2 - P^2_{atm} = \frac{Q_v P^* \mu}{2\pi k_a} \frac{1}{\sqrt{r^2 + (z - z')^2}} \qquad (2\text{-}22)$$

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

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

where

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

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

(12) The effects of atmospheric and impermeable boundaries can be simulated using the method of images. Recognizing $P^2 - P^2_{atm}$ 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 2-6)

$$P^2 - P^2_{atm} = \frac{Q_v P^* \mu}{2\pi k_a (L - l)} \ln\left(\frac{z - l + \sqrt{r^2 + (z - l)^2}}{z - L + \sqrt{r^2 + (z - L)^2}} \cdot \frac{z + L + \sqrt{r^2 + (z + L)^2}}{z + l + \sqrt{r^2 + (z + l)^2}}\right) \qquad (2\text{-}24)$$

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 $z = 2b + L$

$$P^2 - P^2_{atm} = \frac{Q_v P^* \mu}{2\pi k_a (L - l)} \left\{ \ln\left(\frac{z - l + \sqrt{r^2 + (z - l)^2}}{z - L + \sqrt{r^2 + (z - L)^2}} \cdot \frac{z + L + \sqrt{r^2 + (z + L)^2}}{z + l + \sqrt{r^2 + (z + l)^2}}\right) + \ln\left(\frac{z - 2b + L + \sqrt{r^2 + (z - 2b + L)^2}}{z - 2b + l + \sqrt{r^2 + (z - 2b + l)^2}} \cdot \frac{z + 2b + l + \sqrt{r^2 + (z + 2b + l)^2}}{z + 2b + L + \sqrt{r^2 + (z + 2b + L)^2}}\right)\right\} \qquad (2\text{-}25)$$

which requires a corresponding sink/source pair at $r = 0$, $z = -2b + L$ to $-2b + l$ and $r = 0$, $z = -2b - l$ to $-2b - L$

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L - l)} \left\{ \ln\left(\frac{z - l + \sqrt{r^2 + (z-l)^2}}{z - L + \sqrt{r^2 + (z-L)^2}} \cdot \frac{z + L + \sqrt{r^2 + (z+L)^2}}{z + l + \sqrt{r^2 + (z+l)^2}} \right) \right.$$
$$+ \ln\left(\frac{z - 2b + L + \sqrt{r^2 + (z-2b+L)^2}}{z - 2b + l + \sqrt{r^2 + (z-2b+l)^2}} \cdot \frac{z - 2b - L + \sqrt{r^2 + (z-2b-L)^2}}{z - 2b - l + \sqrt{r^2 + (z-2b-l)^2}} \right) \qquad (2\text{-}26)$$
$$\left. - \ln\left(\frac{z + 2b - l + \sqrt{r^2 + (z+2b-l)^2}}{z + 2b - L + \sqrt{r^2 + (z+2b-L)^2}} \cdot \frac{z + 2b + l + \sqrt{r^2 + (z+2b+l)^2}}{z + 2b + L + \sqrt{r^2 + (z+2b+L)^2}} \right) \right\}$$

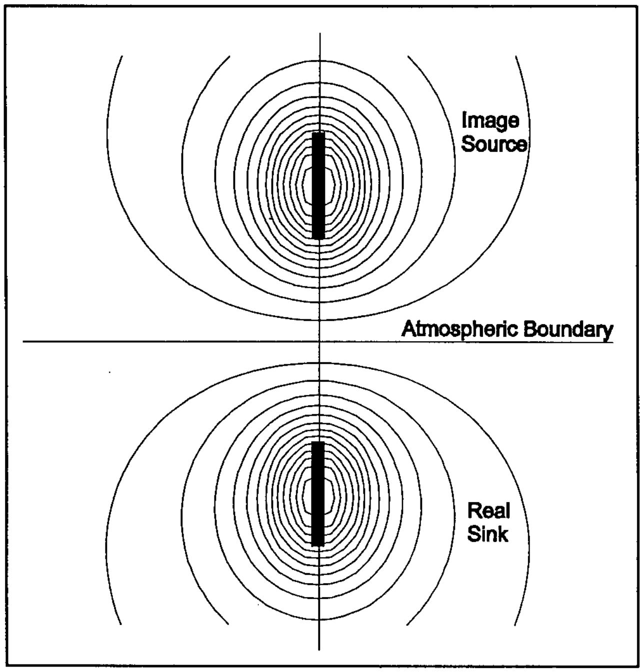


Figure 2-6. Use of superposition to simulate an atmospheric boundary

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 2-27). 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 2-27 is shown on Figure 2-7. King (1968) solved the same problem using the Dirac delta function, resulting in a slightly more complicated solution.

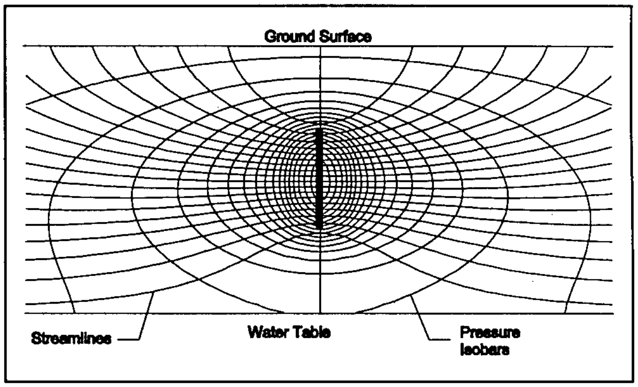


Figure 2-7. Streamlines and pressure isobars

(13) 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

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

$$- \sum_{n=1}^{\infty} (-1)^n \ln \left(\frac{z - 2nb + L + \sqrt{r^2 + (z - 2nb + L)^2}}{z - 2nb + l + \sqrt{r^2 + (z - 2nb + l)^2}} \cdot \frac{z - 2nb - L + \sqrt{r^2 + (z - 2nb - L)^2}}{z - 2nb - l + \sqrt{r^2 + (z - 2nb - l)^2}} \right. \tag{2-27}$$

$$\left. \left. \cdot \frac{z + 2nb - L + \sqrt{r^2 + (z + 2nb - L)^2}}{z + 2nb - l + \sqrt{r^2 + (z + 2nb - l)^2}} \cdot \frac{z + 2nb + L + \sqrt{r^2 + (z + 2nb + L)^2}}{z + 2nb + l + \sqrt{r^2 + (z + 2nb + l)^2}} \right) \right\}$$

air permeability tensor), and performing the coordinate transformation

$$r' = r\sqrt{\frac{k_z}{k_r}}; \tag{2-28}$$

$$z' = z$$

Air flow equations (e.g., Equation 2-27) can be solved in the transformed coordinate system using a transformed air permeability

$$k' = \sqrt{k_r \cdot k_z} \tag{2-29}$$

at which point the resulting pressure (or stream function) values can be translated back into the original coordinate system using Equations 2-28.

(14) 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 2-20

$$P^2 - P_{atm}^2 = \sum_{i=1}^{n} \frac{Q_i P_i^* \mu}{\pi b k_a} \ln \frac{r_{e_i}}{\sqrt{(x - x_i)^2 + (y - y_i)^2}} \tag{2-30}$$

where

n = number of wells

Q_i = volumetric flow rate from the i^{th} well [L^3/T]

P_i = reference pressure for the i^{th} flow rate [M/LT^2]

r_{ei} = radius of pressure influence for the i^{th} well [L]

x_i = x-coordinate of the i^{th} well

y_i = y-coordinate of the i^{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 2-27

$$
\begin{aligned}
P^2 - P_{atm}^2 = \sum_{l=1}^{m} \frac{Q_i P_i^{*} \mu}{4 \pi k_a (L_i - l_i)} \Bigg\{ \ln \Bigg[& \frac{(z - l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - l_i)^2}}{z - L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - L_i)^2}} \\
& \cdot \frac{z + L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + L_i)^2}}{z + l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + l_i)^2}} \Bigg] \\
- \sum_{n=1}^{\infty} (-1)^n \ln \Bigg[& \frac{z - 2nb + L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb + L_i)^2}}{z - 2nb + l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb + l_i)^2}} \\
& \cdot \frac{z - 2nb - L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb - L_i)^2}}{z - 2nb - l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - 2nb - l_i)^2}} \\
& \cdot \frac{z + 2nb - L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb - L_i)^2}}{z + 2nb - l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb - l_i)^2}} \\
& \cdot \frac{z + 2nb + L_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb + L_i)^2}}{z + 2nb + l_i + \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z + 2nb + l_i)^2}} \Bigg] \Bigg\}
\end{aligned} \tag{2-31}
$$

where

l_i = depth to the top of the well screen at the i^{th} well

L_i = depth to the bottom of the well screen at the i^{th} well

m = number of wells

A plot of pressure isobars generated using Equation 2-31 is shown on Figure 2-8.

(15) 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-Rieman equations, which apply to functions satisfying the LaPlace equation. In two-dimensional Cartesian coordinates, the Cauchy-Rieman equations can be written as:

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}; \quad \frac{\partial \phi}{\partial y} = -\frac{\partial \phi}{\partial x} \tag{2-32}$$

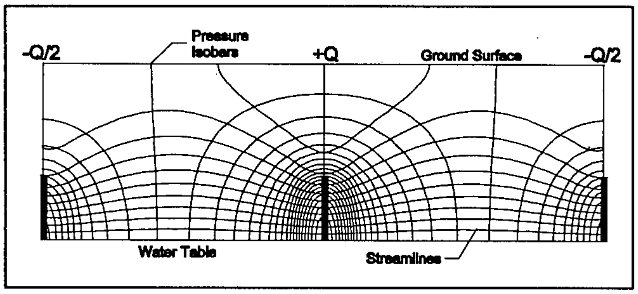


Figure 2-8. Streamlines and pressure isobars for a multiwell system

where

Φ = LaPlace potential

ψ = stream function

Recognizing $P^2 - P_{atm}^2$ as a LaPlace potential, stream functions can be obtained by performing the integration:

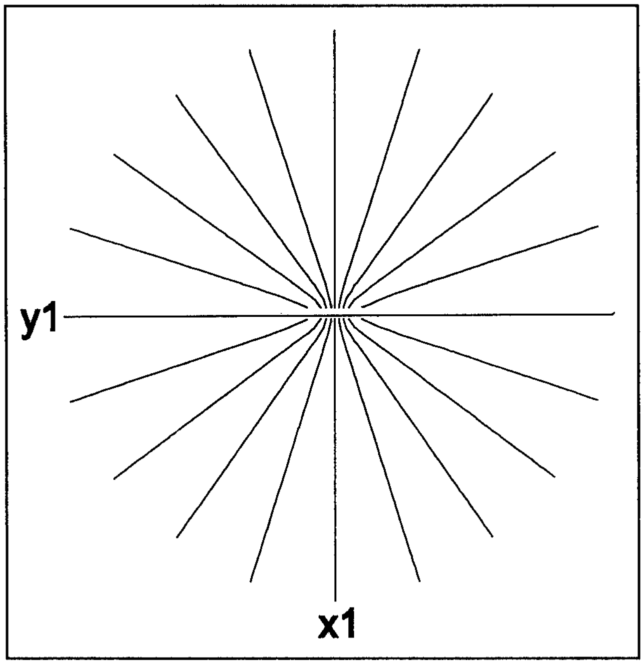


Figure 2-9. Streamlines for one-dimensional radial flow

$$\psi = \int \frac{\partial (P^2 - P_{atm}^2)}{\partial y} dx \qquad (2\text{-}33)$$

Stream functions are useful for evaluating flow paths and travel times for vapor flow. Applying Equation 2-33 to the equation for one-dimensional radial flow (Equation 2-20) in Cartesian coordinates yields:

$$\psi = \frac{Q_v P^* \mu}{\pi b k_a} \tan^{-1}\left(\frac{y - y_1}{x - x_1}\right) + C_1 \qquad (2\text{-}34)$$

where

C_I = a constant of integration

Equation 2-34 represents a family of straight lines passing through (x_1, y_1), where the arctangent term is equivalent to the angle θ (in radians) between each line and the positive x-axis (Figure 2-8). Defining the angle θ as:

$$\theta = \tan^{-1} \left| \frac{y - y_1}{x - x_1} \right| \qquad (2\text{-}35)$$

unique values of ψ can be specified for all θ by defining the constant of integration so as:

$$\begin{aligned}
\psi &= \frac{Q_v P^* \mu}{\pi b k_a} \theta \quad for\ 0 < \theta < \frac{\pi}{2}; \\
\psi &= \frac{Q_v P^* \mu}{\pi b k_a} (\pi - \theta) \quad for\ \frac{\pi}{2} < \theta < \pi; \\
\psi &= \frac{Q_v P^* \mu}{\pi b k_a} (\pi + \theta) \quad for\ \pi < \theta < \frac{3\pi}{2}; \\
\psi &= \frac{Q_v P^* \mu}{\pi b k_a} (2\pi = \theta) \quad for\ \frac{3\pi}{2} < \theta < 2\pi
\end{aligned} \qquad (2\text{-}36)$$

In two-dimensional radial coordinates, the Cauchy-Rieman equations can be written as:

$$\frac{\partial \psi}{\partial z} = r \frac{\partial \phi}{\partial r}; \quad \frac{\partial \psi}{\partial r} = -r \frac{\partial \phi}{\partial z} \qquad (2\text{-}37)$$

Applying Equation 2-37 to the equation for two-dimensional radial flow (Equation 2-37) yields:

$$
\begin{aligned}
\psi = \frac{Q_v P^* \mu}{4\pi k_a (L-l)} r \Bigg\{ \Bigg[& \frac{r-(z-L)+\sqrt{r^2+(z-L)^2}}{r+(z-L)+\sqrt{r^2+(z-L)^2}} - \frac{r-(z-l)+\sqrt{r^2+(z-l)^2}}{r+(z-l)+\sqrt{r^2+(z-l)^2}} \\
& - \frac{r-(z+L)+\sqrt{r^2+(z+L)^2}}{r+(z+L)+\sqrt{r^2+(z+L)^2}} + \frac{r-(z+l)+\sqrt{r^2+(z+l)^2}}{r+(z+l)+\sqrt{r^2+(z+l)^2}} \Bigg] \\
- \sum_{n=1}^{\infty} (-1)^n \Bigg[& \frac{r-(z-2nb+L)+\sqrt{r^2+(z-2nb+L)^2}}{r+(z-2nb+L)+\sqrt{r^2+(z+2nb+L)^2}} - \frac{r-(z-2nb+l)+\sqrt{r^2+(z-2nb+l)^2}}{r+(z-2nb+l)+\sqrt{r^2+(z-2nb+l)^2}} \\
& + \frac{r-(z-2nb-L)+\sqrt{r^2+(z-2nb-L)^2}}{r+(z-2nb-L)+\sqrt{r^2+(z-2nb-L)^2}} - \frac{r-(z-2nb-l)+\sqrt{r^2+(z-2nb-l)^2}}{r+(z-2nb-l)+\sqrt{r^2+(z-2nb-l)^2}} \\
& - \frac{r-(z+2nb+L)+\sqrt{r^2+(z+2nb+L)^2}}{r+(z+2nb+L)+\sqrt{r^2+(z+2nb+L)^2}} + \frac{r-(z+2nb+l)+\sqrt{r^2+(z+2nb+l)^2}}{r+(z+2nb+l)+\sqrt{r^2+(z+2nb+l)^2}} \\
& + \frac{r-(z+2nb-L)+\sqrt{r^2+(z+2nb-L)^2}}{r+(z+2nb-L)+\sqrt{r^2+(z+2nb-L)^2}} - \frac{r-(z+2nb-l)+\sqrt{r^2+(z+2nb-l)^2}}{r+(z+2nb+l)+\sqrt{r^2+(z+2nb-l)^2}} \Bigg] \Bigg\}
\end{aligned}
\qquad (2\text{-}38)
$$

Equation 2-38 is equaivalent to the stream function obtained by Shan, Falta, and Javandel (1990). A plot of streamlines generated using Equation 2-38 is shown in Figure 2-7.

As described in paragraph 2-4*c*(14), stream functions for multiple well systems can be evaluated by superposition of Equation 2-36 or 2-38. A plot of streamlines for a multiple well system is shown in Figure 2-8.

(16) 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:

$$t = \int \left(\frac{1}{q_s}\right) ds \qquad (2\text{-}39)$$

where

s = distance along a streamline, and

q_s = seepage velocity

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

$$q_s = \frac{k_a}{n_a \mu} \nabla P \qquad (2\text{-}40)$$

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:

$$\frac{dP}{dr} = \frac{Q_v \mu}{2\pi b k_a r} \qquad (2\text{-}41)$$

which can be integrated using Equation 2-39 to obtain:

$$t = \frac{\pi r^2 b n_a}{Q_v} \qquad (2\text{-}42)$$

Equation 2-42 is equivalent to the pore volume of a cylinder surrounding an extraction well, divided by the discharge of the well.

For compressible flow, the integration indicated by Equation 2-39 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.

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.

Brailey (1995, unpublished data) provides travel times at the water table for a vadose zone with an upper atmospheric boundary and a lower impermeable boundary. These travel times are useful for evaluating the required flow rate where the maximum extent of contamination occurs near the water table. The travel times are provided in dimensionless form, using the method of Shan, Falta, and Javendel (1992).

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

$$\nabla \cdot (k_a \nabla P^2) = 2 n_a \mu \frac{\partial P}{\partial t} \qquad (2\text{-}43)$$

(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-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) proposed linearizing Equation 2-14 by expressing P^2 as the product of atmospheric pressure P_{atm} and a deviation from that pressure P'. The resulting equation expressed in one-dimensional radial coordinates is

$$\nabla \cdot (k_a \nabla P') = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P'}{\partial t} \qquad (2\text{-}44)$$

(3) Equation 2-44 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 2-44 is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial P'}{\partial r} \right) = \frac{n_a \mu}{k_a P_{atm}} \frac{\partial P'}{\partial t} \qquad (2\text{-}45)$$

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

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} \int_u^{\infty} \frac{e^{-x}}{x} dx \qquad (2\text{-}46)$$

where

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

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

$$u = \frac{r^2 n_a \mu}{4 k_a P_{atm} t} \qquad (2\text{-}47)$$

(a) The integral in Equation (2-46) 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 2-46 can be approximated using the first two terms of a Taylor series expansion. Using this approximation, Equation 2-46 reduces to:

$$P - P_{atm} = \frac{Q_v \mu}{4\pi b k_a}\left(\ln\frac{4k_a P_{atm} t}{r^2 n_a \mu} - 0.5772\right) \tag{2-48}$$

Equation 2-48 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).

Equations 2-46 through 2-48 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:

$$\frac{\partial^2 P}{\partial r} + \frac{1}{r}\frac{\partial P}{\partial r} - \frac{L\mu}{k_a \rho g b} = \frac{n_a \mu}{k_a P_{atm}}\frac{\partial P}{\partial t} \tag{2-49}$$

where L is the leakage rate.

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

$$L = \frac{k_v \rho g}{\mu}\frac{(P - P_{atm})}{b_v} \tag{2-50}$$

Subsituting L into Equation 2-49 yields:

$$\frac{\partial^2 P}{\partial r} + \frac{1}{r}\frac{\partial P}{\partial r} - \frac{k_v}{k_a}\frac{(P - P_{atm})}{b b_v} = \frac{n_a \mu}{k_a P_{atm}}\frac{\partial P}{\partial t} \tag{2-51}$$

Introducing a *leakage factor B*, defined by:

$$B = \sqrt{\frac{k_a b_v b}{k_v}} \tag{2-52}$$

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

$$\frac{\partial^2 P}{\partial r} + \frac{1}{r}\frac{\partial P}{\partial r} - \frac{P - P_{atm}}{B^2} = \frac{n_a \mu}{k_a P_{atm}}\frac{\partial P}{\partial t} \tag{2-53}$$

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

$$P - P_{atm} = \frac{Q_v \mu}{4\pi k_a} W(u, \frac{r}{B}) \tag{2-54}$$

where *W(u,r/B)* is the leaky well function (Hantush and Jacob. For vapor flow, the Boltzmann variable *u* is defined in Equation 2-47.

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 2-46), including its Taylor series approximation (Equation 2-48), 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 2-48) predicts that the pressure difference between any two radial distances (provided $u \leq 0.01$) is

$$P_2 - P_1 = \frac{Q_v \mu}{4\pi b k_a}\left(\ln\frac{4k_a P_{atm} t}{r_1^2 n_a \mu} - \ln\frac{4k_a P_{atm} t}{r_2^2 n_a \mu}\right) \tag{2-55}$$

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

$$P_2 - P_1 = \frac{Q_v \mu}{4\pi b k_a}(\ln \frac{r_2}{r_1}) \qquad (2\text{-}56)$$

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 2-10).

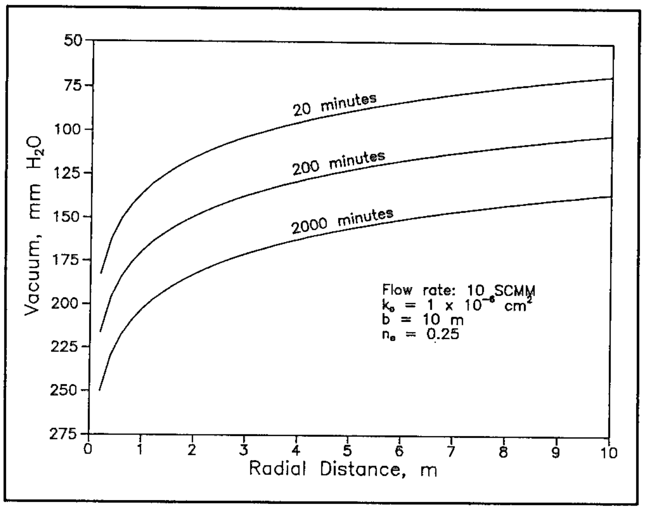


Figure 2-10. Transient pressure distributions calculated using the Cooper-Jacob approximation ($\mu \leq 0.01$)

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.

2-5. Biodegradation Kinetics

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

$$R = -\frac{VC}{K+C} \qquad (2\text{-}57)$$

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 being consumed. Oxygen is assumed not to be limiting because abundant oxygen is provided to the unsaturated zone during BV. Reaction rate versus substrate concentration is sketched in Figure 2-11.

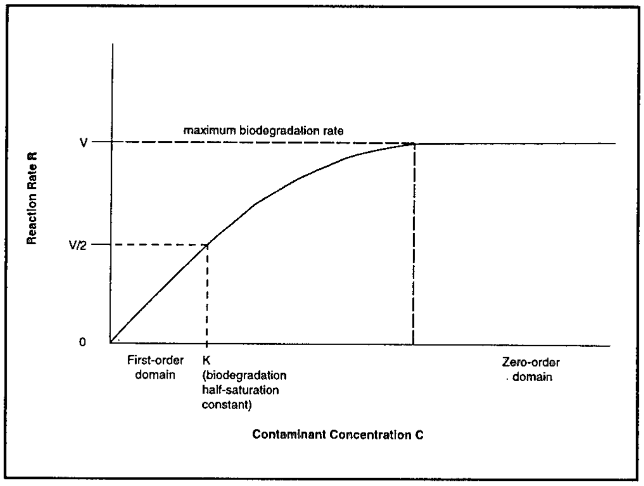


Figure 2-11. Biodegradation reaction rate as a function of substrate concentration

(1) 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

$$R = -V \qquad (K << C) \qquad (2\text{-}58)$$

(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

$$R = -FC \qquad (K >> C) \qquad (2\text{-}59)$$

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

$$C_t = C_o \exp(-Ft) \tag{2-60a}$$

$$\ln(\frac{C_t}{C_o}) = -Ft \tag{2-60b}$$

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

$$\ln(0.5) = -Ft_{1/2} \tag{2-61a}$$

$$t_{1/2} = \frac{0.693}{F} \tag{2-61b}$$

(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 2-60a 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) 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 may be more practical to focus attention on oxygen respiration rather than on contaminant degradation kinetics. Oxygen con centrations 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 4-2*g*(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 2-43 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 2-57). 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 which can contribute significantly to all phases of the project. Readily available models are summarized in Appendix C. Use of models throughout the 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 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 spacings 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 estimation of a broad range of permeabilities, porosities, gas constants, gas molar masses, and viscosities to obtain maximum and minimum estimates of required vapor production rates and numbers of extraction points. Contact between the modelers and the site characterization team is strongly encouraged. Screening modeling typically requires 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 Hyper-Ventilate 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 form $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 which 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, these models are used by experienced modelers.

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. Some large SVE/BV systems are anticipated to operate for several years.

(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 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 in this scenario 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."

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.

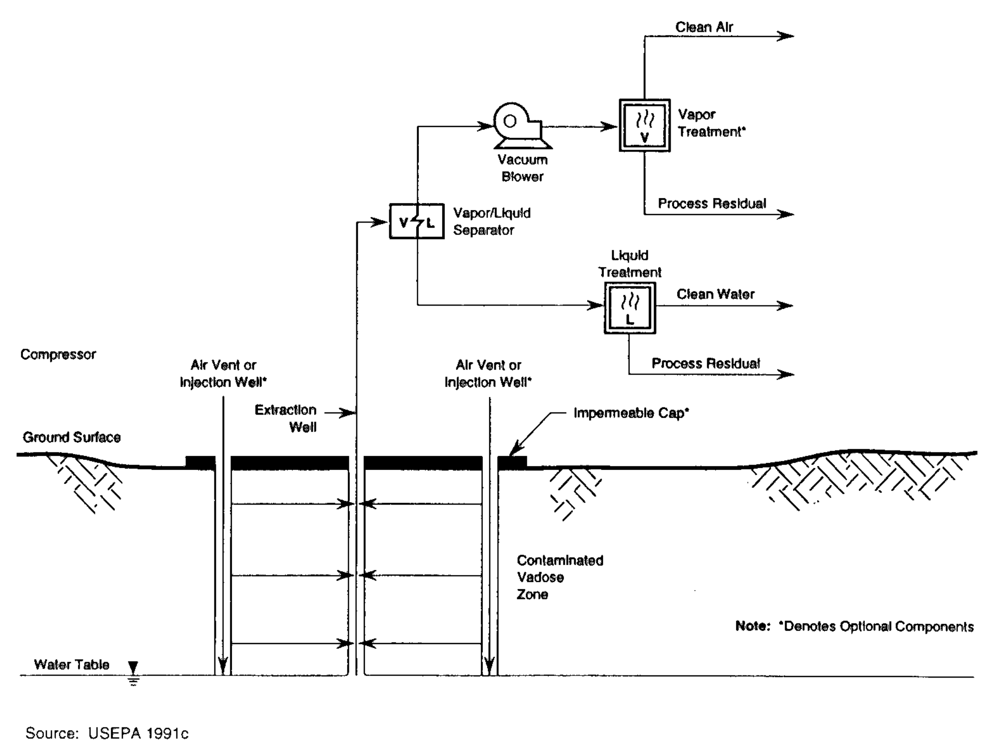
(2) SVE is often used in conjunction with other remediation technologies which treat the resulting contaminated air and water streams. Sometimes ancillary technologies such as soil heating and subsurface fracturing are also used in an effort to further enhance transport rates. SVE is usually required 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 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). Only recently has SVE been used to remediate hazardous waste sites (Lewis 1993). Some of the early applications of SVE to solvents and other hazardous wastes are summarized in USEPA (1989a). USEPA lists six Superfund Remedial Actions at which SVE has been completed, including a 53,500 m^3 portion of the Rocky Mountain Arsenal contaminated with tetrachloroethylene (PCE) and 1,480,000 m^3 at Fairchild Semiconductor contaminated with chlorinated hydrocarbons (USEPA 1993b). SVE is widely used in Europe and has been used at several thousand sites in Germany (Hiller 1991).

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 (Hoeppel, Hinchee, and Arthur 1990). Compounds that are readily aerobically



Source: USEPA 1991c

Figure 3-1. Generic soil vapor extraction system

biodegradable in the vadose zone include linear (and some branched) alkanes; 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 off-gas treatment (Figure 3-2); however, air 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 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

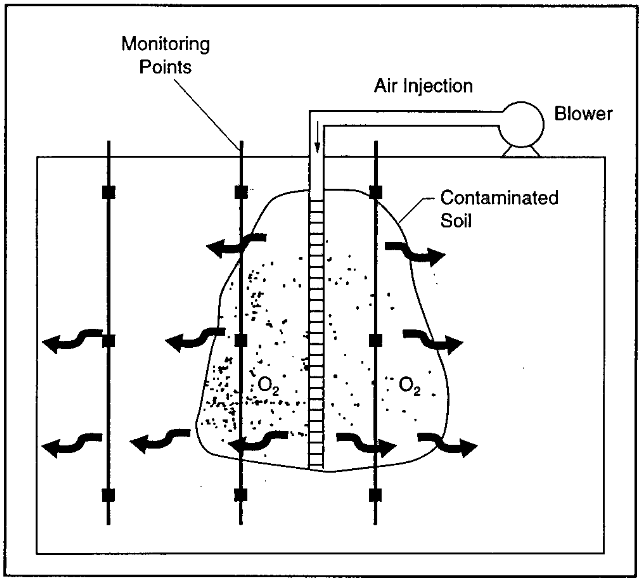


Figure 3-2. Typical bioventing system (AFCEE 1994)

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).

(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. 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 (Ostendorf and Kampbell 1991), but at rates dependent on oxygen diffusion (Ostendorf and Kampbell 1989). BV has recently been implemented at numerous field sites. In May 1992, the U.S. Air Force began an initiative to test BV at 55 contaminated sites throughout the United States and extended the initiative to over 135 sites in December 1992. Initial data have been compiled for approximately 60 of the sites (Miller et al. 1993) and are summarized later in paragraph 3-4. The U.S. Air Force lists three sites at which BV has been completed as of February 1994, including a 95,000-liter spill of JP-4 to a depth of approximately 18 meters at Hill AFB, Utah (AFCEE 1994a).

c. 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 nonbiodegradable 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 5-2*a*, provides further guidance pertaining to the design of combined SVE/BV systems.

d. Dual recovery. Frequently the use of SVE or BV is contemplated in subsurface zones whose pores are nearly or fully saturated with water and/or with NAPL. In such instances, steps that can be taken to deal with these liquids include dual phase recovery, whereby both gas and liquid are extracted simultaneously from the same or adjacent wells. This section briefly reviews the conditions calling for, and methods of implementing, dual phase recovery.

(1) Ambient conditions favorable to dual recovery. Under nearly saturated conditions, such as in medium- and fine-textured soils close to the water table, SVE and BV may not initially be effective. Such soils tend to have a relatively thick capillary fringe, within which soil pores are occupied by water and/or NAPL and thus not open to airflow. A characteristic of the capillary fringe is that liquids within it are at negative gauge pressures (paragraph 2-3*c*), thus they cannot drain by gravity into a large pore such as a well or trench. The forces that retain liquids within and above the capillary fringe are capillary forces of adhesion and cohesion (Hillel 1980a). The finer a soil's texture, the thicker will be its capillary fringe (Lohman 1972). Furthermore, when enough light NAPL (LNAPL) has been released at a site for it to reach the capillary fringe, a sizable fraction tends to occupy that

zone. Whether occupied by water or NAPL, soils having capillary fringe thicknesses of 0.3 meter or more, such as soils with textures of fine sand or finer, are especially good candidates for dual recovery systems. Some practitioners also use dual recovery systems in coarse-textured deposits having very small capillary fringe thicknesses.

(2) Upwelling. The level of a water table (i.e., piezometric surface, defined as the level at which water is in equilibrium with atmospheric pressure) will shift upward toward a vacuum well screened in the unsaturated zone, a phenomenon termed "upwelling" (Johnson et al. 1990a; USEPA 1991d). The maximum rise in the water table will occur at the location where the influence of the applied vacuum is greatest, as at, or just below, a vertical SVE well. The potential rise in the water table that can occur will be equal to the vacuum at that location expressed as an equivalent water column height (i.e., in cm H_2O). The vertical limit of upwelling, z (cm), can thus be calculated as the effective applied vacuum in the well, V_w, in cm H_2O. Therefore, if the bottom of an SVE well is situated within a vertical distance z of the water table, groundwater may be sucked into the well.

(a) Upwelling is not a great concern in permeable formations, where V_w will tend to be small. In less permeable formations, however, upwelling can be significant. Large values of V_w will be required to try to induce airflow. Separation of the bottom of the well screen from the water table will act to attenuate the vacuum felt by the water table; thus, in low permeability material, well depths should not closely approach the water table.

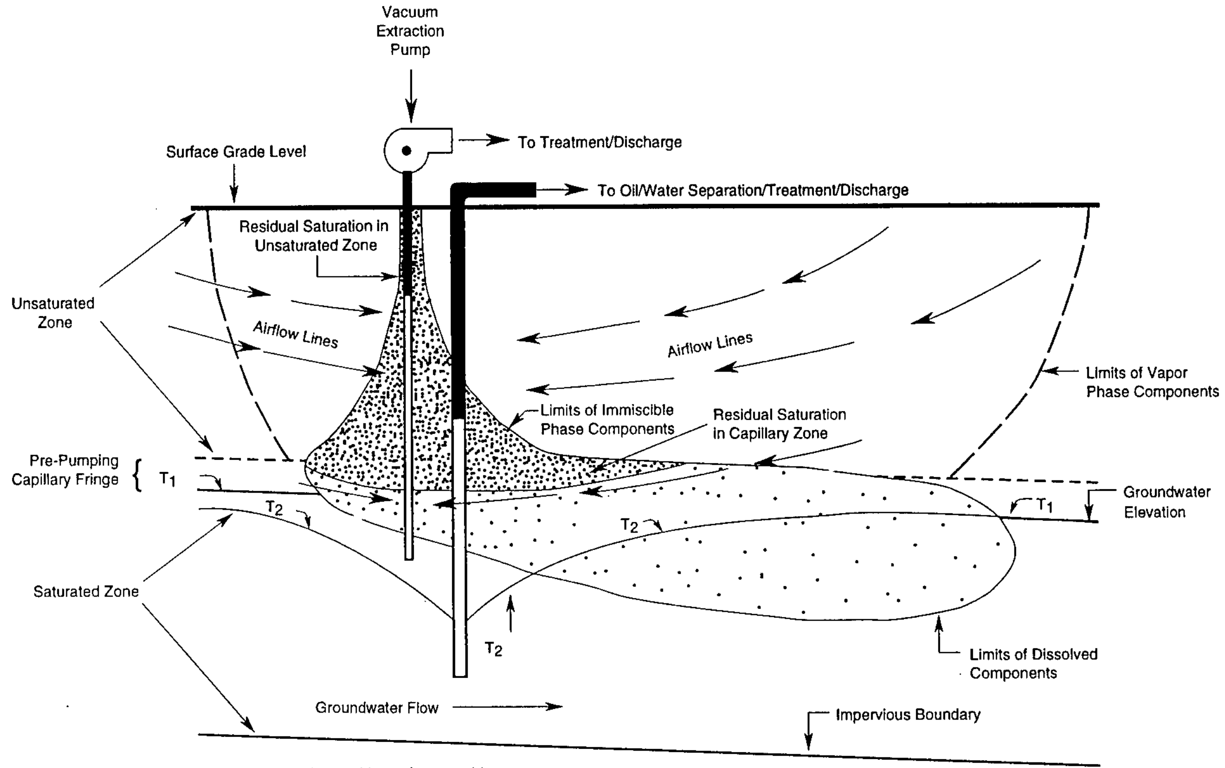
(b) Despite the fact that many SVE modelers adopt the assumption that the liquid phase above the water table is immobile, water and NAPL in the unsaturated zone have been observed to undergo redistribution in response to application of a vacuum (Baker and Wiseman 1992; Baker and Bierschenk 1995). Such observations are consistent with Equation 2-5, by which a reduction in air-phase pressure will decrease the air-water—and air-oil—capillary pressures as well. Accordingly, as the water table translates upward during upwelling, so too will the associated capillary fringe. In such a case, the water table and capillary fringe can be induced to upwell to the point where previously unsaturated soil, and even the well screen itself, can become inundated, blocking airflow to the well.

(3) Dual phase recovery systems. Dual phase recovery systems involve the combined extraction of vapor and liquids from the subsurface, for the purposes of controlling upwelling, dewatering the soil to enhance SVE/BV, and recovering/treating NAPL if present. Such systems are an outgrowth of vacuum wellpoint technologies that have long been employed by construction dewatering engineers to enhance the drainage of water retained by capillary forces in medium- to fine-textured soils. Dual phase recovery is something of a misnomer in that three separate phases are frequently extracted, water, NAPL, and vapor (Baker 1995).

(a) Several major variations of dual-phase recovery are used with SVE/BV: (1) separate liquids and vapor extraction wells, as when conventional groundwater recovery wells are placed near SVE wells to control the degree of upwelling (Figure 3-3); (2) separate liquids and vapor extraction conduits within the same well, such that the applied vacuum on the well enhances the flow of both liquids and gases into the well (Figure 3-4); and (3) combined fluids extraction via a single conduit within a well, a process termed "slurping" because of its similarity to the familiar act of suctioning liquid and air from a glass with a soda straw. When slurping is conducted in the subsurface with the dual aims of enhancing free-product recovery and stimulating bioventing, it is termed "bioslurping" (AFCEE 1994b; Kittel et al. 1994; Hoeppel et al. 1995).

(b) Bioslurper. The left- and right-hand sides of Figure 3-5 contrast conventional LNAPL recovery using a two-pump system, with a bioslurper system. In the conventional approach, the position of the pump below the ambient water table creates a cone of depression, resulting in hydraulic gradients that cause water and NAPL to flow toward the well. While NAPL that flows into the well is recoverable by skimming, NAPL that becomes entrapped or "smeared" within the cone of depression is not readily recovered. By contrast, the bioslurper uses a suction tube positioned at the NAPL-water interface to induce a pressure gradient causing water, NAPL, and vapor to flow into the well, without creating a cone of depression or "smearing." With slurping or bioslurping, the volume of extracted groundwater (often requiring treatment prior to discharge) is less than with the conventional two-pump approach or variation (2) above. Meanwhile the recovery of LNAPL is often enhanced (Blake and Gates 1986; Hayes, Henry, and Testa 1989; Kittel et al. 1994). When liquids and vapor recovery are combined, water and/or NAPL that is drawn into the well is typically lifted and conveyed to an oil-water separator situated aboveground.

(c) The amount of NAPL remaining in the soil after conventional free-product recovery has ceased to be effective tends to be especially large and hard to remove in



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

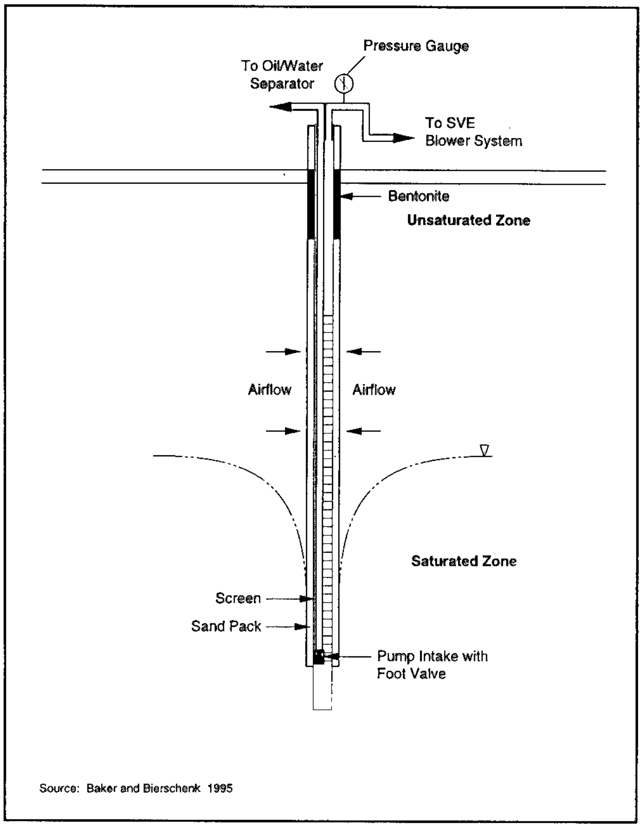
Source: Adapted from Hoag 1991

Figure 3-3. Dual recovery schematic

medium- and fine-textured materials (having K_s values of 10^{-5} to 10^{-7} m s^{-1}). Inducing airflow through such soils when they are nearly saturated can be difficult; therefore, SVE/BV may not work initially. By applying a vacuum to a combination recovery well, however, capillary forces holding NAPL and water within the soil pores above residual saturations can, to a certain extent, be overcome (Baker and Bierschenk 1995). Thus some of the NAPL and water that would otherwise remain within the porous medium can be siphoned into the well and pumped to the surface. In dual phase recovery, vadose zone water and NAPL can be extracted without the risk of smearing NAPL into a cone of depression.

(d) Once NAPL and water have been reduced to residual saturations and continuous air-filled pathways have been established in the soil through which air can flow, SVE and BV begin to be effective. Even after that point, however, dual phase recovery can continue to be useful in reducing upwelling, especially during times of high groundwater elevation. A disadvantage of dual recovery is the need to address treatment of extracted groundwater and air prior to discharge. The reader is cautioned that air lifting certain liquids (e.g., jet fuel) could create an explosive hazard due to the generation of static electricity amid an explosive atmosphere in the holding tank.

e. 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).



Source: Baker and Bierschenk 1995

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

(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 some cases the entire soil pile is covered by a synthetic liner. 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 3-2*c* also apply here. Figures 3-6 and 3-7 illustrate a typical soil pile design (see also Athey and Wrenn 1993).

(2) 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 meter. 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 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.

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

(1) Air sparging. Air sparging, also referred to as “in situ air stripping” or “in situ volatilization,” 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, 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).

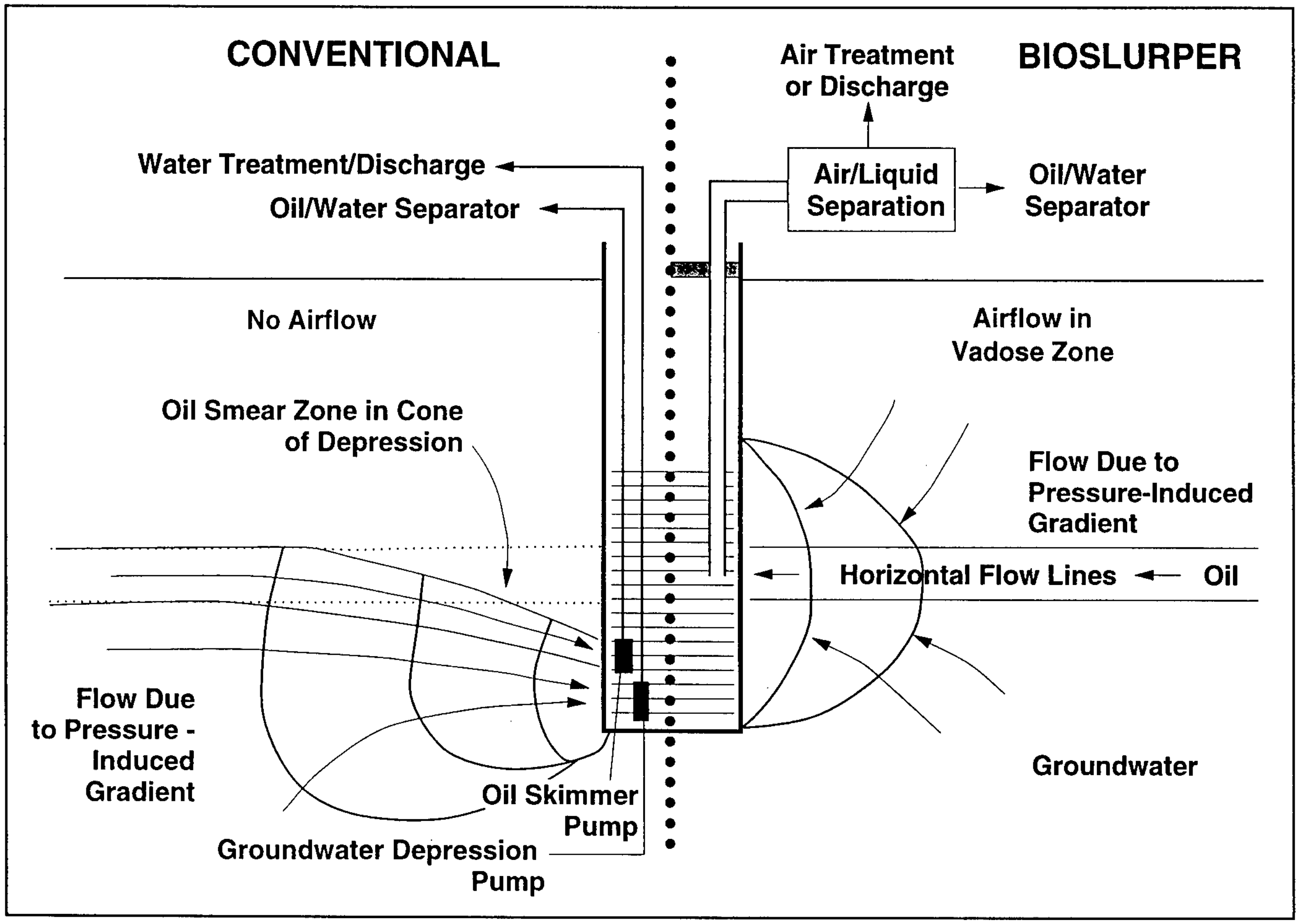


Figure 3-5. Comparison of LNAPL remediation using conventional two-pump system (left) and bioslurper system (right) (after Kittel et al. 1994)

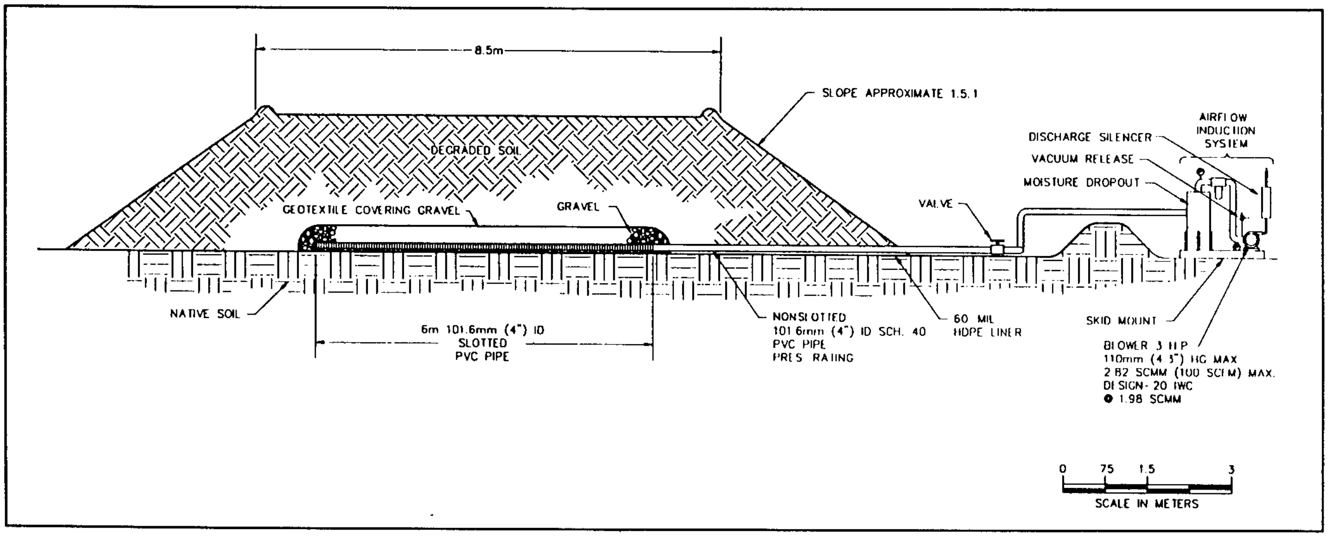


Figure 3-6. Aboveground soil pile (cross section)

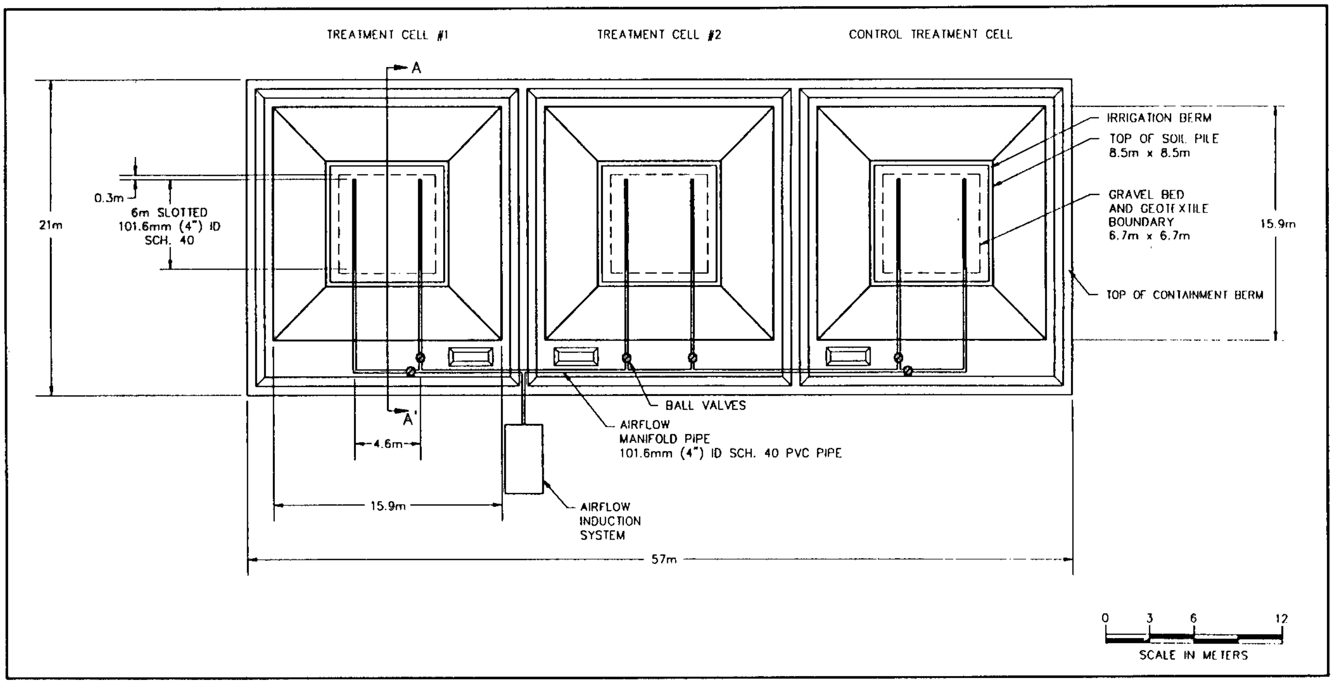


Figure 3-7. Aboveground soil piles (plan view)

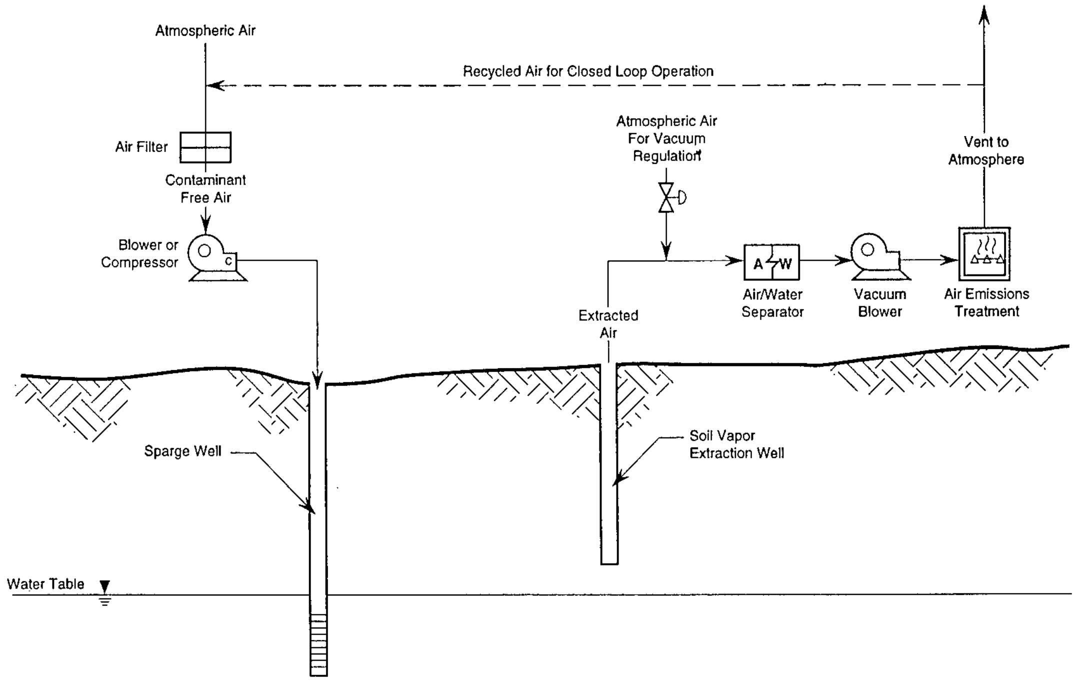
(a) Air sparging systems are often used in conjunction with SVE so that the volatile contaminants stripped from the saturated zone can be captured or biodegraded upon reaching the vadose zone. Due to the positive pressure gradient induced by the injection of air, the use of air sparging without SVE could 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 reportedly 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 exhibiting VOC contamination. Design considerations include depth to groundwater, contaminant solubility, biodegradability, and 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 3-8 (USEPA 1992).

(d) Currently there is considerable debate as to the effectiveness of air sparging (Hinchee 1994). Few data sets are comprehensive enough to demonstrate that sparged air has become well distributed within the treatment zone rather than flowing through preferential pathways and thus bypassing significant portions of the treatment zone (Baker, Hayes and Frisbie 1995). The degree to which air sparging increases dissolved oxygen levels in portions of the saturated zone is also being debated. More widespread use of discrete monitoring points will be needed to resolve this issue.

(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



Source: USEPA 1992

Figure 3-8. Air sparging process schematic

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 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). More information will be available after completion of the integrated demonstration, which is scheduled for 1994.

(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, helium, and methane (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).

(c) Sulfur hexafluoride (SF_6) is often used as a tracer. Gas chromatography analysis of 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, Patuxent River, Fallon, and Eielson U.S. Air Force Bases to distinguish gaseous diffusion from oxygen consumption by aerobic microorganisms (Hinchee, Ong, and Hoeppel 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) 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.

(a) Techniques that have been field tested for increasing subsurface temperatures include: radio frequency heating (RF), six-phase soil heating, steam injection, resistive heating, and hot air injection. Other potential in situ heating techniques can also be considered based upon site-specific availability of heating sources.

(b) Heating contaminated soil using RF electrical energy to a temperature of 80 to 300 °C 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. The cost of the process is a function of soil volume, soil moisture content, and final treatment temperature, among other factors (Sresty, Der, and Houthoofd 1992).

(c) Six-phase soil heating (SPSH) is a technique that uses common low-frequency electricity to heat soils as an enhancement to SVE (Gauglitz et al. 1994a, b). The mechanism of heating is resistive dissipation of the electrical energy. SPSH uses conventional single-phase transformers to convert standard three-phase electricity into six-phase electricity. Electrodes are inserted into the ground in one or more circular arrays of six per array. Each electrode is connected to a separate transformer wired to provide it with a separate current phase. 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 much as one-fifth to one-tenth those for RF heating or microwave heating (Gauglitz et al. 1994b). SPSH has been demonstrated in the field at a site containing very low permeability clay soils contaminated with PCE and TCE, as part of the Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration at the Savannah River Site, SC. 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. Considering the 1,100 m^3 of soil that was heated to above 70°C, the energy input requirement during the demonstration was 90 kWh/m^3 (Gauglitz et al. 1994a). SPSH also shows promise for enhancement of BV (Heath and Truex 1994).

(d) Steam injected into a series of boreholes creates thermal gradients that expedite volatilization and subsequent removal by SVE. According to Miller (1975), the movement of the steam front is controlled mainly by temperature gradients and the heat capacity of the porous media, and less so by pressure gradients and permeability. The use of steam injected at depth has been shown to create upward thermal gradients which can facilitate the removal of contaminants by SVE (Adams, Smith, and Basile 1992). Steam stripping of contaminants from groundwater can also be followed by SVE (Evans 1991).

(e) 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. Heat can also be introduced using buried heating cables or by infiltration of heated water (Sayles et al. 1992).

(4) 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 is a very recent development for creating fractures in soil or rock to increase 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). 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 6 meters in radius. A viscous mixture of sand (termed a "propant"), 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 from 1.5 to 9 meters below the ground surface.

(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 propant 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 3-9. A host of other technologies should initially be screened along with technologies involving SVE and BV.

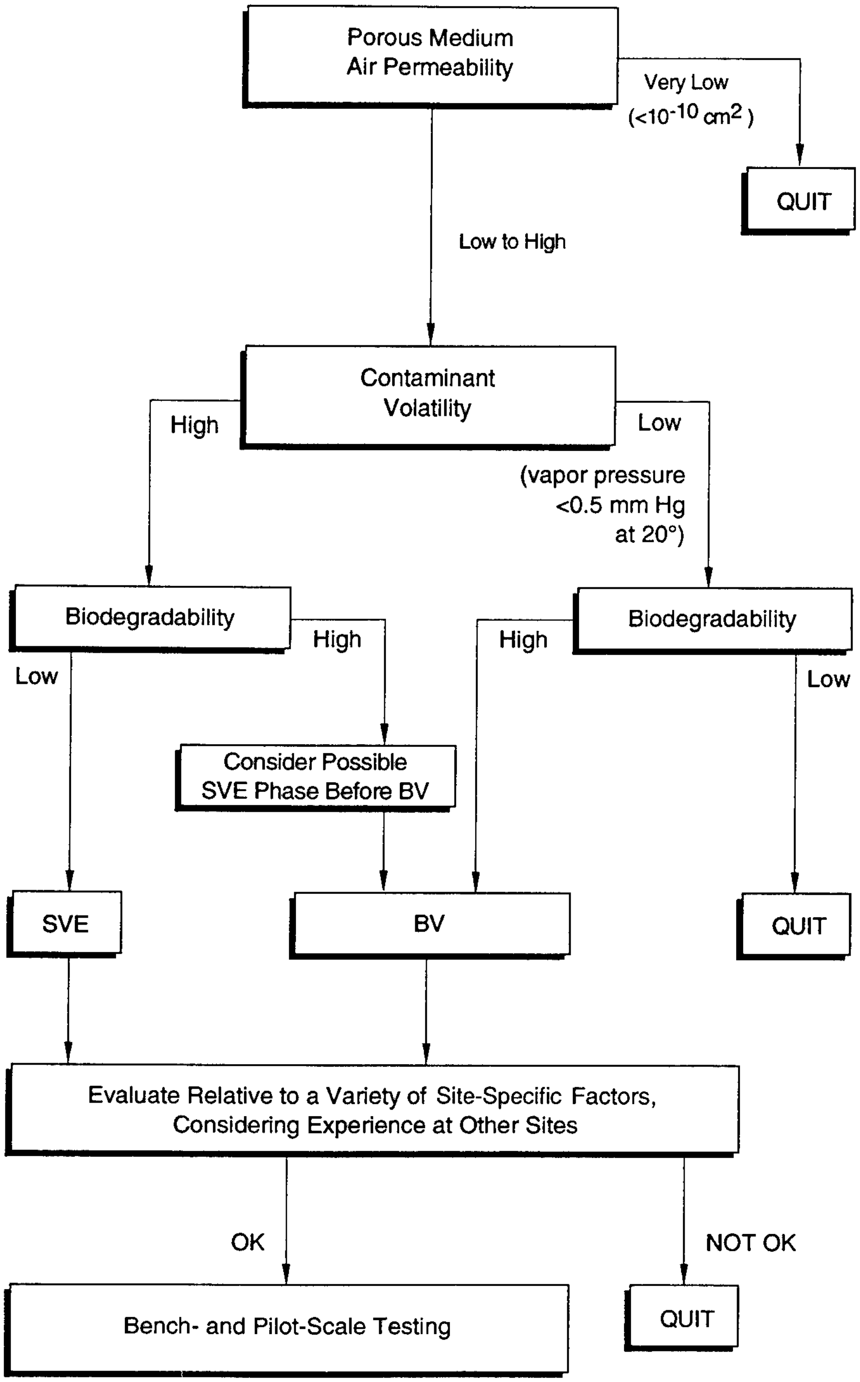
a. Approach to technologies. An integrated approach to SVE/BV and other technologies is preferred. For example, SVE/BV may be considered as part of a remediation system which also includes groundwater and product recovery. It is therefore critical that data be collected to address the feasibility of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

b. Site conditions.

(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 which 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.

(2) 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. The nature of surface horizons are noteworthy. 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).

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 which 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



Relevant Information (EM Paragraph No.)

Air permeability (3-3e)
Moisture content (3-3g)

Quit unless inclusion of porous medium fracturing or water table drawdown is warranted; also may want to consider BV or SVE in aboveground piles

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Vapor pressure (2-3b)
Henry's Law constant (2-3b)
Boiling point (2-3b)

Solubility (2-3b)
Biodegradation half-life and other data (2-5)

Initial and required contaminant concentrations (3-3c)
Stratigraphy and heterogeneity (3-3e)
Depth to groundwater (3-2d)
Presence of NAPL (3-3c)
Moisture content/retention (3-3g)
Temperature (3-3f)
Organic carbon content (3-3f)
Bioventing only: (3-2b, 3-3h)
  Toxic inhibitors
  Nutrient concentrations
  O_2 and CO_2 concentrations

Figure 3-9. Technology screening decision tree

Table 3-1
Testing and Analytical Method Summary

Parameter	Collection Method	Analytical Method
Air-phase permeability (core-scale)	In situ or undisturbed 50- to 75-mm-diameter soil sample typical	See paragraph 4-2*d* 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
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	EPA Method 415.1; Churcher and Dickhout (1989)
Moisture content (saturation)	Neutron access tube measurements	Neutron gauge (Gardner 1986)
	Tensiometers Undisturbed 50- to 75-mm-diameter soil sample	Cassel and Klute (1986) 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)
Depth to groundwater and seasonal variations	Water table monitoring wells	Water level meter or interface gauge and surveyed well elevations
Volatile hydrocarbon content in soil gas	In situ	Downey and Hall (1994); ASTM D3416-78
O_2 content in soil gas	In situ	Portable meter, electrochemical cell method
CO_2 content in soil gas	In situ	Portable meter, infrared adsorption method
Microbial respiration rate	In situ	Hinchee et al. 1992
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 9040 or 9045
Nitrate/nitrite-nitrogen	Split spoon or other soil sample	EPA Method 353.2
Ammonia-nitrogen	Split spoon or other soil sample	EPA Method 350.2
Total Kjeldahl nitrogen	Split spoon or other soil sample	EPA Method 351.3
Total and ortho phosphorus	Split spoon or other soil sample	EPA Method 365.2

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 2-3*b*.

(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

Table 3-2
VOCs Considered to be Amenable to SVE

Halogenated Volatile Organics	
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	
Nonhalogenated Volatile Organics	
Ketones/Furans	Acetone Methyl Ethyl Ketone Methyl Isobutyl Ketone
Aromatics	Benzene Ethyl Benzene Styrene Toluene m-Xylene o-Xylene 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

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

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

Contaminant Groups		Example of Contaminants	Effectiveness
Organics	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
Inorganics	Volatile metals	Mercury, tetraethyl lead	c
	Nonvolatile metals	Nickel, chromium	c
	Asbestos		c
	Radioactive materials		c
	Inorganic corrosives		c
	Inorganic cyanides	Sodium cyanide	c
Reactive	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.
* Demonstrated effectiveness on some compounds in the contaminant group.

Source: U.S. EPA 1991c

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.

(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) 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) SAP: USACE 1994. *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 and laboratory analysis methods is also provided. Table 3-4 lists the topics covered in the SAP.

(3) SAP: USACE 1990. *Chemical Data Quality Management for Hazardous Waste Remedial Activities.* ER 1110-1-263. This regulation contains instruction for site-specific implementation of the Chemical Data Quality Management requirements.

(4) USEPA Environmental Compliance Branch 1991f. *Standard Operating Procedures and Quality Assurance Manual*, Revision 1. NTIS No. PB91-233650. 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 1987a. *Data Quality Objectives for Remedial Response Activities:* EPA/540/G-87/003. (NTIS No. PB88-131370). The DQOs formalized in the SAP will address the objectives in terms of the six data quality indicators: precision; accuracy; completeness; representativeness; comparability; and, where applicable, method detection limit. Usually, different DQOs are developed for the different phases of site characterization and SVE/BV implementation consistent with the intended use of the data. For example, for field methods used in soil gas surveys, the objectives of precision, accuracy, and method detection limit are generally not as rigorous as for

Table 3-4
SAP Format Requirements

Title Page
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Introduction
Changes from Approved SAP

I Field Sampling Plan

Title Page
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- 1.0 Site Background
  - 1.1 Site Location and History
  - 1.2 Historical and Current Land Use
  - 1.3 Previous Investigations
- 2.0 Scope and Objectives of the Investigation
- 3.0 Field Investigation Rationale
  - 3.1 Geophysics
    - 3.1.1 Method Proposed and Rationale
    - 3.1.2 Study Area Definition and Measurement Spacing and Rationale
  - 3.2 Soil Gas Survey
    - 3.2.1 Soil Gas Sample Locations
    - 3.2.2 Sample Collection, and Field and Laboratory Analysis
    - 3.2.3 Background, QA/QC, and Blank Samples and Frequency
  - 3.3 Ground Water Investigation
    - 3.3.1 Monitoring Well Location and Installation
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    - 3.3.3 Upgradient, QA/QC, and Blank Samples and Frequency
  - 3.4 Subsurface Soil Investigation
    - 3.4.1 Soil and Rock Boring Locations
    - 3.4.2 Discrete/Composite Soil Sampling Requirements
    - 3.4.3 Sample Collection, and Field and Laboratory Analysis
    - 3.4.4 Background, QA/QC, and Blank Samples and Frequency
  - 3.5 Surface Soil and Sediment Investigation
    - 3.5.1 Surface Soil Sample Locations
    - 3.5.2 Sediment Sample Locations from Onsite and/or Offsite Drainage Channels
    - 3.5.3 Sediment Sample Locations from Ponds, Lakes, and Lagoons
    - 3.5.4 Discrete/Composite Soil and/or Sediment Sampling Requirements
    - 3.5.5 Sample Collection, and Field and Laboratory Analysis
    - 3.5.6 Upgradient, QA/QC, and Blank Samples and Frequency
  - 3.6 Surface Water Investigation
    - 3.6.1 Surface Soil Sample Locations
    - 3.6.2 Sample Collection, and Field and Laboratory Analysis
    - 3.6.3 Upgradient, QA/QC, and Blank Samples and Frequency
  - 3.7 Other Matrices, etc.
    - 3.7.1 Sample Locations
    - 3.7.2 Discrete/Composite Sampling Requirements
    - 3.7.3 Sample Collection, and Field and Laboratory Analysis
    - 3.7.4 Background/Upgradient, QA/QC, and Blank Samples and Frequency
- 4.0 Specific Investigation Activities
  - 4.1 Geophysics
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    - 4.1.5 Measurement Point/Grid Surveying
    - 4.1.6 Data Processing
    - 4.1.7 Potential Interpretation Techniques

(Sheet 1 of 4)

Table 3-4
(Continued)

- 4.2 Soil Gas Surveys
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  - 4.2.2 Materials (casing, screen, etc.)
  - 4.2.3 Installation
  - 4.2.4 Sampling Methods
  - 4.2.5 Field Measurement Procedures and Criteria (if applicable)
  - 4.2.6 Documentation
- 4.3 Ground Water
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    - 4.3.1.1 Drilling Methods and Equipment
    - 4.3.1.2 Materials
      - 4.3.1.2.1 Casing/Screen
      - 4.3.1.2.2 Filter Pack, Bentonite, Grout
      - 4.3.1.2.3 Surface Completion
      - 4.3.1.2.4 Water Source
      - 4.3.1.2.5 Delivery, Storage, and Handling of Materials
    - 4.3.1.3 Installation
      - 4.3.1.3.1 Test Holes
      - 4.3.1.3.2 Soil Sampling and Rock Coring During Drilling
      - 4.3.1.3.3 Geophysical Logging
      - 4.3.1.3.4 Borehole Diameter and Depth
      - 4.3.1.3.5 Filter Pack Placement
      - 4.3.1.3.6 Bentonite Seal
      - 4.3.1.3.7 Cement/Bentonite Grout Placement
      - 4.3.1.3.8 Concrete/Gravel Pad Placement
      - 4.3.1.3.9 Protective Cover Placement
      - 4.3.1.3.10 Well Identification
      - 4.3.1.3.11 Well Development
      - 4.3.1.3.12 Well Survey
      - 4.3.1.3.13 Alignment Testing
      - 4.3.1.3.14 In situ Permeability Testing
    - 4.3.1.4 Documentation
      - 4.3.1.4.1 Logs and Well Installation Diagrams
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side-by-side confirmatory samples to be laboratory analyzed or in groundwater sample analyses for contaminants that may be migrating offsite. That is because the soil gas survey results do not need to be as precise and accurate to be valuable in characterizing the site in a cost-effective manner. In following the DQO guidance, the decision makers work with the field sampler, the laboratory, and the design engineer to determine the DQOs needed for each phase of the project. For determination of compliance with final cleanup levels, fairly rigorous DQOs are invoked.

(6) DQO: USEPA 1993f. *Data Quality Objectives Process for Superfund. Interim Final Guidance.* EPA/540/G-93/071. Publication 9355.9-01. This document describes the process through which the decision makers and technical team together develop qualitative and quantitative statements that describe the problems and the certainty and uncertainty that the decision makers are willing to accept in the results derived from the environmental data. One focus of the process is to arrive at "If..., Then..." statements (called decision rules) that guide action based on sampling and analysis results.

(7) 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.

(8) 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.

(9) 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.

(10) 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 C_{12} to C_{17} diesel, compositing may result in the loss of 10 to 20 percent of the diesel mass. References and guidance documents pertaining to development of sampling and analysis plans, including selection of sampling locations, collection techniques, and standard operating procedures (SOPs), are listed below.

- Flatman et al. 1984. *Geostatistical Strategy for Soil Sampling: the Survey and the Census, Environmental Monitoring and Assessment.* Volume 4, pp. 335-49.

- Mason 1983. *Preparation of Soil Sampling Protocol - Techniques and Strategies.* EPA-600/4-83-020 (NTIS No. PB83-206979).

- New Jersey Department of Environmental Protection and Energy 1992. *Field Sampling Procedures Manual.* Available from the Maps and Publications Sales Office, Bureau of Revenue, CN 417, Trenton, NJ 08625. (609) 777-1038.

- USEPA 1986. *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods.* EPA/SW-846.

- USEPA 1988c. *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA.* EPA/540/G-89/004.

- USEPA 1989b. *Soil Sampling Quality Assurance User's Guide.* Second Edition, EPA/600/8-89/046 (NTIS No. PB89-189864).

- USEPA 1991b. *Compendium of ERT Soil Sampling and Surface Geophysics Procedures.* OSWER Directive 9360.4-02 (NTIS No. PB91-9211273).

- USEPA 1991g. *Soil Sampling and Analysis for Volatile Organic Compounds.* EPA/540/4-91/001.

(11) 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.
- USEPA 1987b. *Compendium of Methods for the Determination of Toxic Compounds in Ambient Air.* EPA/600/4-84-041.
- USEPA 1988b. *Field Screening Methods Catalog.* EPA/540/2-88/005.
- USEPA 1990a. *Contract Laboratory Program - Statement of Work for Analysis of Ambient Air (Draft).*

(12) 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 on canisters followed by GC/MS analysis.

(13) 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 quantitative correlation between soil gas and soil concentrations can seldom be obtained, particularly when higher concentrations of residual contaminants are present. When contrasting soil gas and soil sample concentrations it is helpful to keep in mind that soil sample results represent contaminants in only the NAPL and dissolved phases, while soil gas measures only those in vapor. USEPA 1988b and USEPA 1991g above provide guidance on soil gas survey methodology.

(14) Soil gas surveys can also provide an indication of contaminant concentrations which can initially be expected in SVE offgas. Long-term offgas contaminant concentrations, however, are not well predicted by soil gas surveys (see paragraph 4-2*b*(2)).

(15) 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.

(16) Soil gas surveys are often 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.

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 2-3*c*).

(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 which 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 can be measured or estimated by a variety of methods, several of which are presented in paragraphs 4-2*a* and 4-5 and in Appendix D. Soils with air permeabilities less than about 10^{-10} cm^2 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 which 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 5-15).

f. Solid matrix properties. Data on solid matrix properties (introduced in paragraph 2-3*b*) 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 °K increase in temperature.

(2) The fraction of organic carbon in a soil (f_{oc}) affects the ability of a given compound to partition to the gaseous or aqueous phases. Soils characterized by high f_{oc} values have a tendency to limit the amount of mass which partitions from a soil particle to the surrounding pore space. In contrast, soils characterized by low f_{oc} 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, Kreamer, 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), as by passing the injection air through a humidification unit. Moisture content in soil samples can be measured gravimetrically. Moisture 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) 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. One method of preventing soils from becoming desiccated is to humidify the injection air.

(4) 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) A variety of heterotrophic and hydrocarbon degrading bacteria may exist within the unsaturated zone and their occurrence depends upon many factors such as temperature, pH, oxygen content, moisture content, soil chemistry, and the presence of toxic inhibitors such as heavy metals. 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. This is typically accomplished by inoculating plates containing nutrient agar and incubating the plate to promote the growth of visible microbial colonies. Standard methods for plate counts are described in APHA/AWWA/WEF (1992). 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.

(2) 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_2 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.

(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.

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 2-3*c*, 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 2-3*c*). 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.

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.

e. During 1992-1995, the U.S. Air Force is applying BV technology at over 135 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.

f. 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).

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 4-2*g*.) Pilot-scale tests usually measure pressures, flow rates, contaminant concentrations, and other parameters during air pumping tests. If bench-scale tests are not performed, it is recommended that a pilot test be performed at the site to ensure that SVE or BV is an appropriate means to remediate the site.

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 4-7*a* 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 infeasible 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. 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 remedy 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.
- If column tests show SVE can meet goals, conduct field air permeability tests to check implementability of SVE.

- Supplement the above with mathematical modeling.

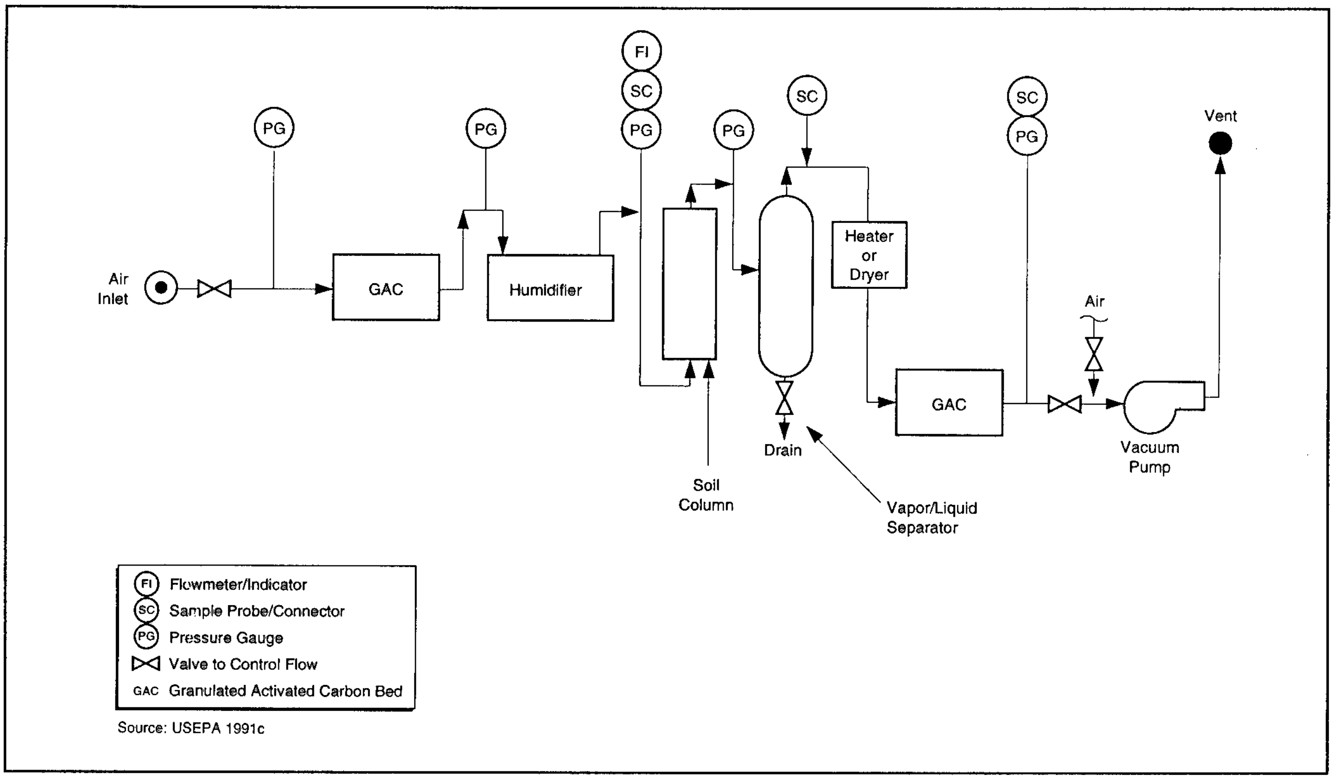
- Conduct pilot-scale testing for remedy selection if warranted.

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 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.

(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.

(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



Source: USEPA 1991c

Figure 4-1. Diagram of typical column test apparatus

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. Diffusional processes are often not properly modeled.
3. Order-of-magnitude air permeability measurements may be obtained with "undisturbed" samples.	3. More accurate 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

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 4-2*g*.

(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 2-3*b*).

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 radius of influence of various vent configurations, 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 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 2-3*c*). 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

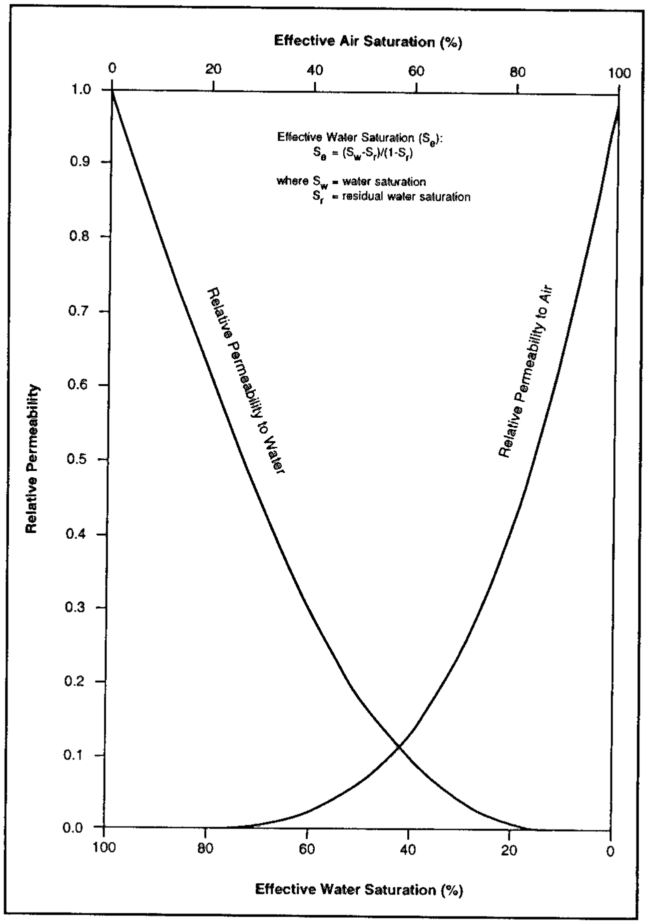
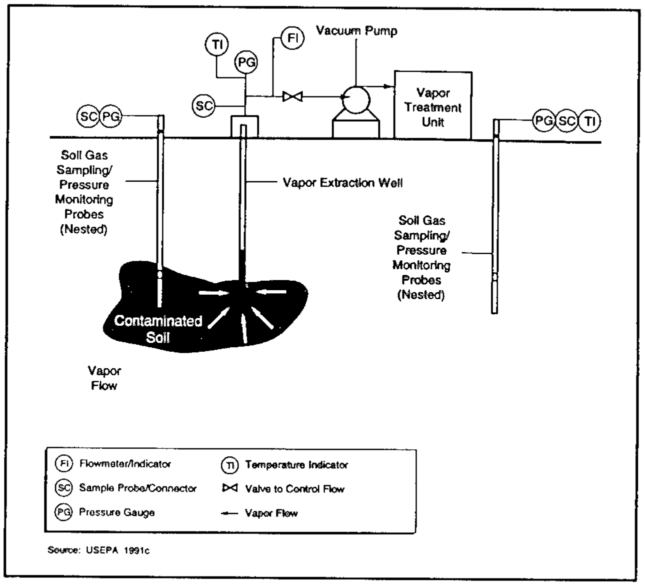


Figure 4-2. Relationship between water saturation and relative permeability to air

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 which show rapid equilibration of measured vacuums (or pressures).

(3) The one-dimensional radial flow solution 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 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 influence.

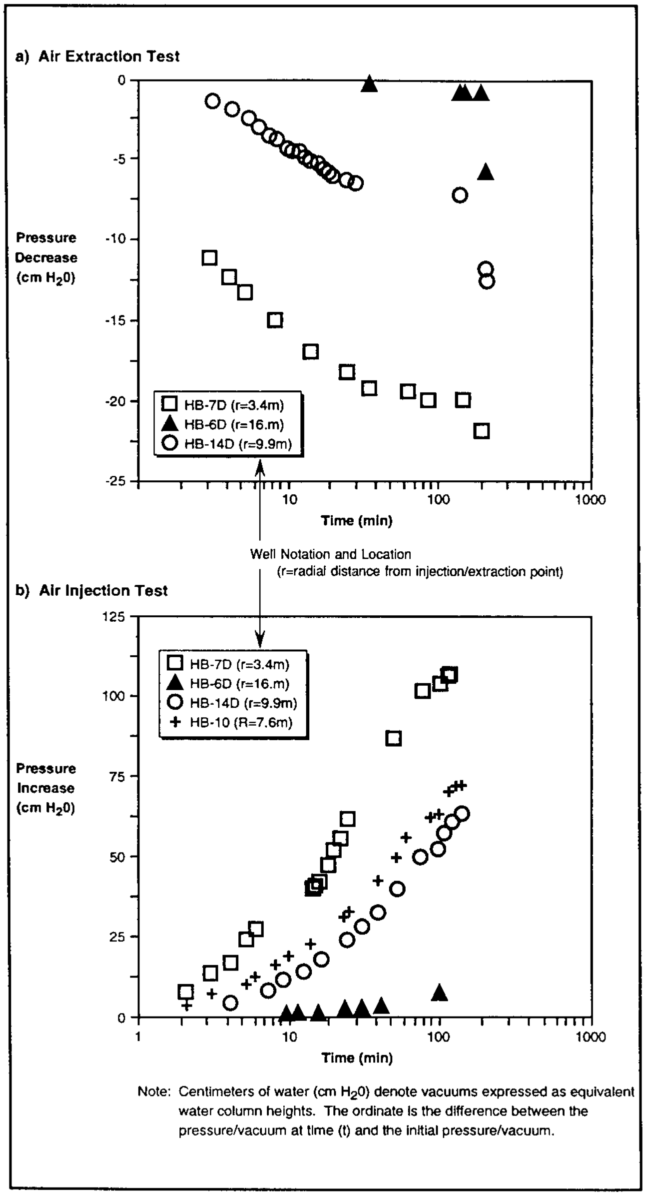


Source: USEPA 1991c

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

(4) It should be noted that open sites and "leaky" sites can also be addressed with analytical solutions. Tests under these boundary conditions are implemented like those conducted under radial flow conditions, except that the well should not be screened as closely to the surface. Refer to procedures outlined in Shan, Falta, and Javendel (1992) for analysis of transient air permeability test data from sites with an air-permeable surface.

(5) The 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. Alternatively, the flow can be maintained at a constant rate and the vacuum measured against time. Stepped-rate tests can be used to develop performance curves for a particular well, and to quantify the increase in well head loss associated with an increase in applied vacuum (or pressure). The results of the air permeability test are then plotted in accordance with the particular solution method used (e.g., Figure 4-4).



Note: Centimeters of water (cm H_20) denote vacuums expressed as equivalent water column heights. The ordinate is the difference between the pressure/vacuum at time (t) and the initial pressure/vacuum.

Figure 4-4. Typical field air permeability test data

(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. 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. These values provide a good check on the values determined by transient methods.

(7) Table 4-2 presents the advantages and limitations of field air permeability tests. The general procedures for conducting 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 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.

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. Does not show the location of NAPL pools.
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: USEPA 1991c

Since the latter considerations are almost impossible to predict, pilot tests are commonly performed to evaluate sustainable baseline concentrations.

(2) The offgas concentration versus time history can, at times, clarify location of the test relative to the contaminant: 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. Refer to other guidance for further information regarding offgas treatment. A sampling port for offgas treatment 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, 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) Collection of confirmatory soil samples is not advocated during or after performance of pilot tests of limited duration. 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^{TM} 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 ^{14}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^{TM} and sodium hydroxide, respectively. Any leachate generated is also analyzed for ^{14}C. At the end of the experiment, the mass balance is completed by extracting the soil with organic solvents and chromic acid to measure remaining 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). Biodegradation 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 points are installed at varying distances from the venting well in the contaminated soil. Each monitoring point is screened to at least three depths. Air with 1 to 2 percent helium is injected for at least 20 hours at a rate of 4.72×10^{-4} to 8.02×10^{-4} cubic meters per second (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. 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 purpose of the helium is to assess the extent of gaseous diffusion within the aerated zone. The in-situ respirometry test is terminated in 5 days or when the oxygen concentration is reduced to 5 percent (Hinchee et al. 1992).

(5) Oxygen uptake rates, corrected for background respiration and diffusion, 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 jet fuel (JP-4) is hexane. An appropriate stoichiometry should be selected for any specific contamination problem. Oxygen uptake rather than carbon dioxide generation is used because nonbiological 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). 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. It can nevertheless be used to guide the decisionmaking 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

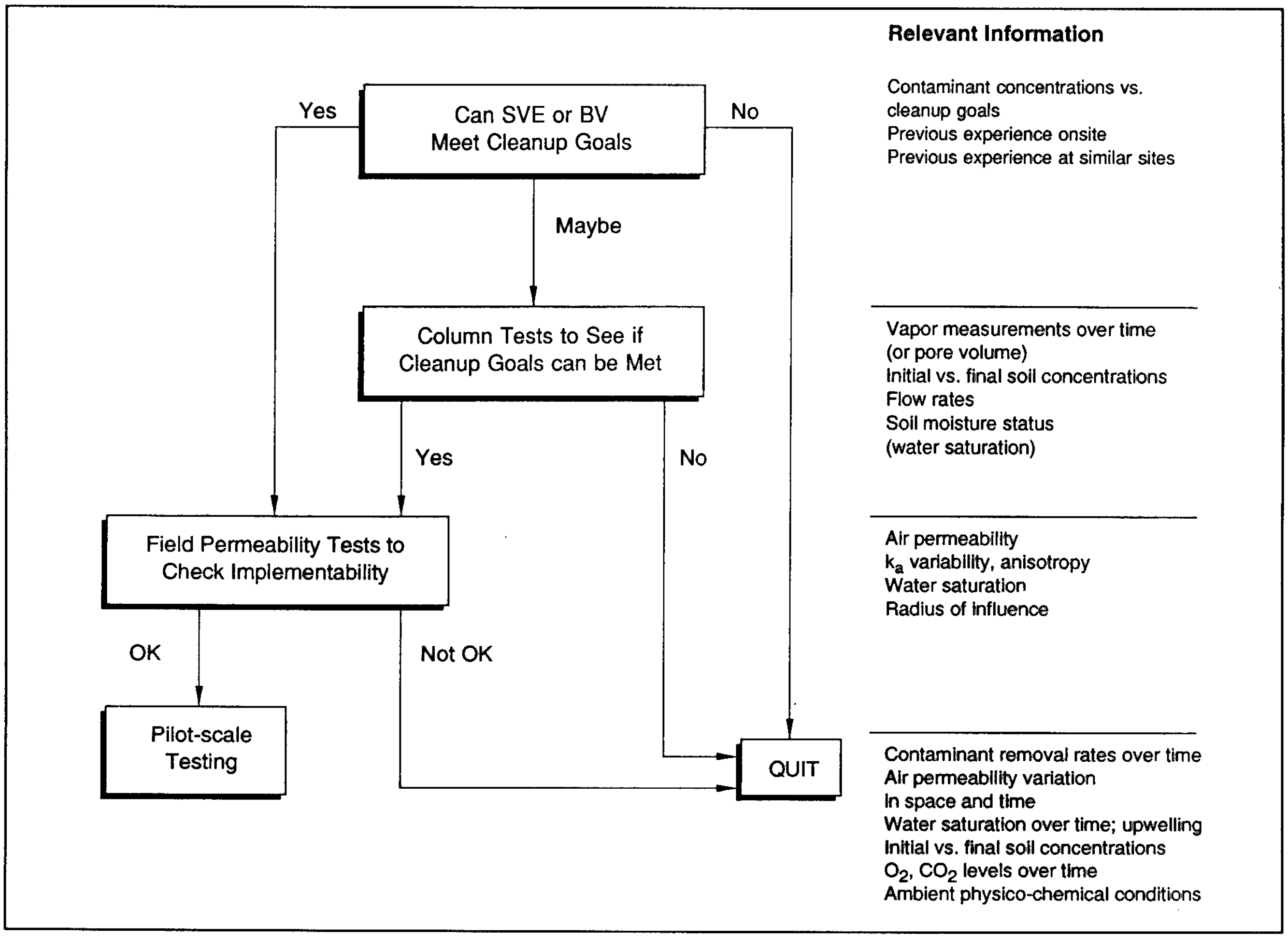


Figure 4-5. Bench- and pilot-scale testing decision tree

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 powerful 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 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.

4-4. Work Plan

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

a. 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.

b. 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).

c. 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.

d. 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 descriptions of equipment, site layout, site selection rationale (ideally the test site will be representative of the area to be remediated by the full-scale SVE/BV system), test procedures, test sequence and duration, anticipated flow rates and contaminants, schematics, sampling and analysis procedures, and Quality Assurance/Quality Control (QA/QC) requirements including DQO.

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

f. 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).

g. 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 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.

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

i. 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 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 (QAPjP), 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.

j. 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).

k. 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.

l. 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.

m. 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. All reports should be in conformance with USACE minimum data reporting requirements.

n. 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 pilot-scale, SVE/BV performance tests.

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

- 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_2, CO_2, and water in recovered vapors.
- Potential effects on the water table and the capillary fringe induced by SVE/BV.

(1) 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.

(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 guidance will suffice (Hinchee et al. 1992).

(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.
- 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.
- Vapor discharge stack.

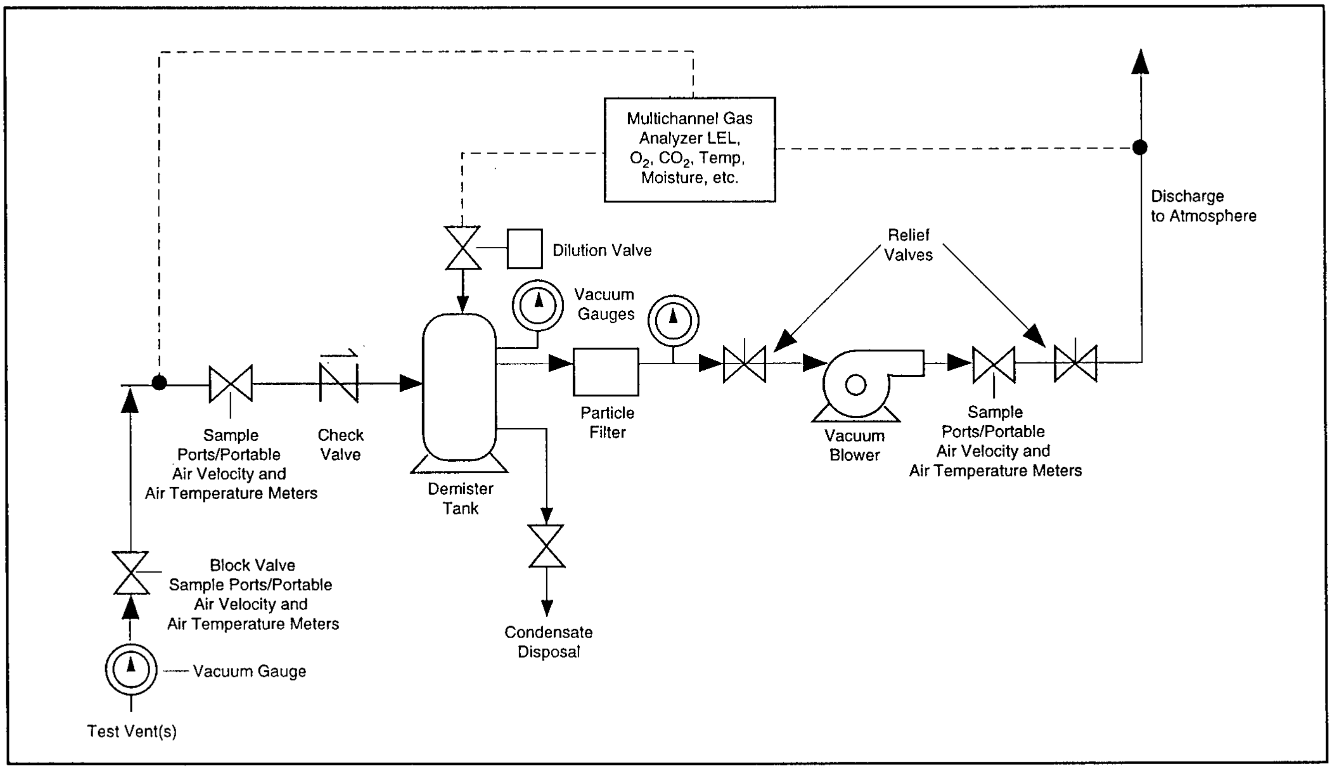


Figure 4-6. SVE/BV system performance test typical process

- Multichannel gas analyzer.
- Barometer.

As a general rule, open sites exhibiting 2-D airflow should have a minimum of three observation probes placed within a radial distance of <2 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; 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 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.

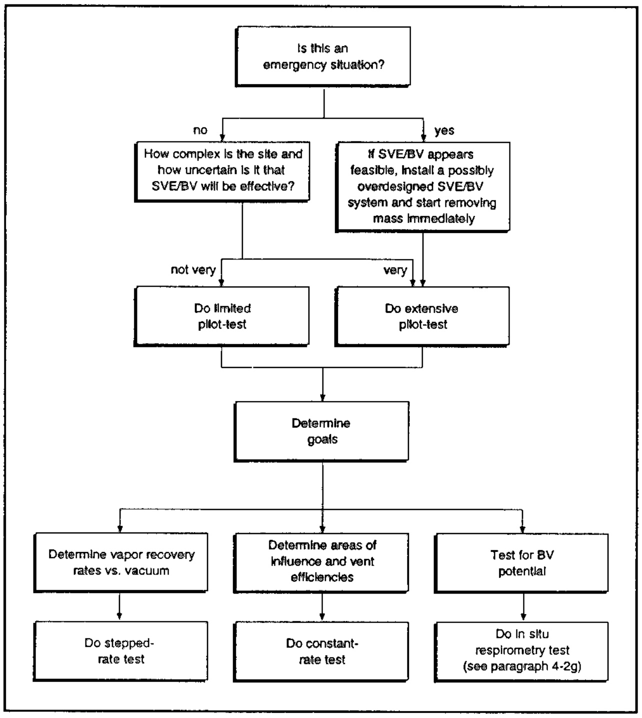


Figure 4-7. Pilot-testing decision tree

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

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

(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 4-2*e* and Appendix D); and 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.

(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 flow rate 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 expansion of the saturated zone above the water table and is induced by the vacuum on the vent. In some cases, the saturated zone rises to the point that the effective length of the vent decreases and restricts flow to the vent. Consequently, the 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).

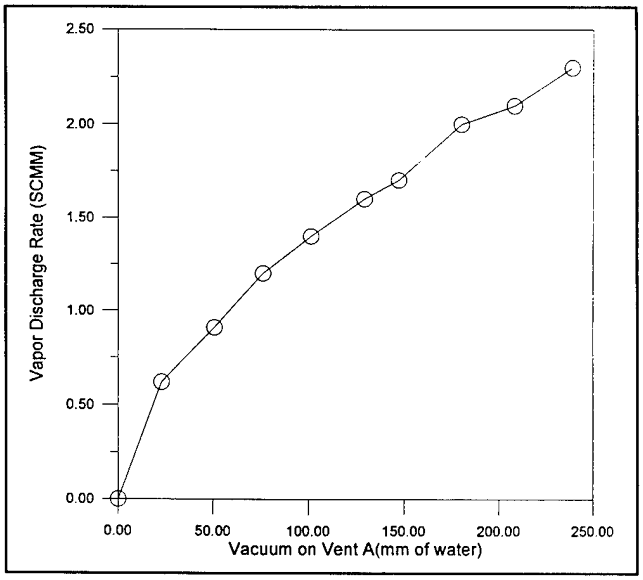


Figure 4-8. Stepped-rate test example for a horizontal vent

(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 a vertical vent can be used to estimate the required vacuum to obtain a target flow rate:

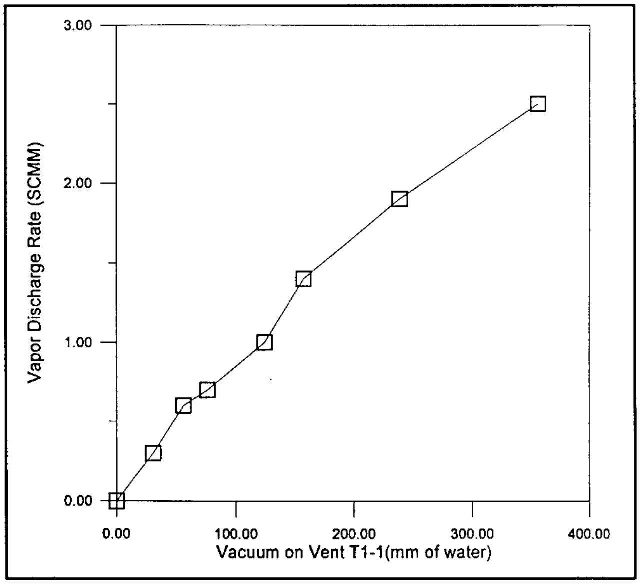


Figure 4-9. Stepped-rate test example for a vertical vent

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

where

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

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

μ_a = viscosity of air $[ML^{-1}\,T^{-1}]$

R_w = radius of test vent [L]

R_I = radius of pressure influence for test vent [L]

L = effective vent length [L]

k_a = estimated air permeability $[L^2]$

P_A = absolute atmospheric pressure $[ML^{-1}\,T^{-2}]$

(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. For example, if the target venting rate required to achieve sufficient removal of VOCs from a site were 3 soil pore volumes per day, then the target flow rate could be roughly estimated by

$$Q_T = \frac{3/day \cdot \pi R_E^2 b n_a}{8.64 X 10^4 sec/day} \tag{4-2}$$

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 4-5*f*(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 capable of applying the required vacuum at the test vent and producing the target flow rate at that vacuum. Depending on the test equipment layout and piping configuration, it may be prudent to factor in head losses in the test equipment itself. As much as 80 to 90 percent of the vacuum can be lost in test equipment piping and through the vent. Consequently, a larger blower may be required to achieve the desired flow rates and vacuums at the vent. Additional information regarding head losses in piping and equipment can be found in paragraph 5-2.

(8) 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.

(9) 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:

- 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, LEL, etc., of vapor in the vent and discharge stack to establish baseline levels
    - Vacuum at demister tank and test vents (should be zero)
- 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 (±10 percent) vacuum and flow rate. The vacuum at the test vent should be increased in approximately 5 to 10 equal increments (in centimeters [cm] of water vacuum) as given by:

$$V_i = i/n \left(1 - \frac{P_{wT}}{P_A}\right) 1{,}033 \tag{4-3}$$

where

V_i = test vent vacuum on the ith step (cm of water)

i = ith step in the test

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

P_{wT} = target absolute pressure at the test vent (g/cm·sec^2)

P_A = absolute atmospheric pressure (~1.01×10^6 g/cm·sec^2)

1,033 = cm of water vacuum

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

- Once the specified P_{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.

(10) 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 a few hours to complete.

(11) 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.

(12) 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 0.0254 cm of water vacuum, whichever is greater. The precision of the vapor flow rates should be equal to about 1/5 of the vent flow rate or 28,300 cm^3 per minute, whichever is greater.

(13) 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.

(14) If the P_{wT} 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.

(15) 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 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.

(16) 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:

$$L = L_o - \left(1 - \frac{P_w}{P_A}\right) 1{,}033 \tag{4-4}$$

where

L = effective screen length (cm) at P_w

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

P_w = absolute pressure at test vent (g/cm·sec^2) (corrected for vacuum loss along well screen and casing, if vacuum is measured at well head)

P_A = absolute atmospheric pressure (~1.01×10^6 g/cm·sec^2)

1,033 = cm of water in one atmosphere

(17) If the initial, effective screen length (L_o) is fairly short, the maximum flow rates will be achieved at

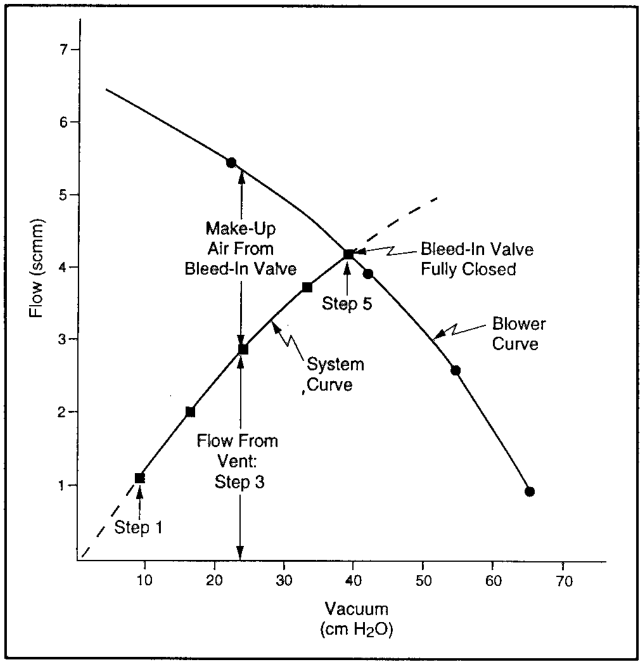


Figure 4-10. Example of system curve construction from stepped rate test

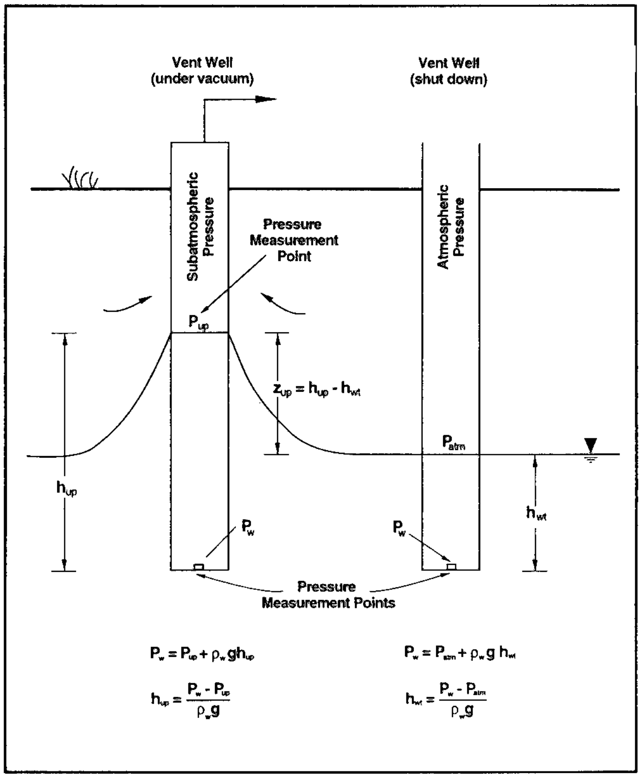


Figure 4-11. Monitoring upwelling

relatively low vacuums and the vent may not be useable for the full-scale SVE/BV system.

(18) 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).

(19) 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.

(20) A method that enables the extent of upwelling to be determined and that incorporates evaluation of the thickness of the capillary fringe is the use of a neutron moisture meter (Gardner 1986; Kramer, Cullen, and Everett 1992; Baker and Bierschenk 1995).

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.

(1) The vent is tested at the highest flow rate obtainable with a test blower as determined by a stepped-rate test (see paragraph 4-5*e*), and the resulting subsurface vacuums are measured at several observation points distributed around the test vent.

(2) The resultant vacuum data are usually plotted and mapped in plan and cross-section view to evaluate the extent and shape of the area of influence of the vent, as well as the vacuum losses attributable to the vent itself (i.e., efficiency). Figures 4-12 and 4-13 provide example results for constant-rate area of influence tests on a vertical and a horizontal vent, respectively. Examples of vacuum measurements with distance from test well are presented in Figure 4-14.

(3) 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 4-5*c* (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.

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

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

where

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) as well as the radius of influence can be estimated as described in paragraph 4-5*e*(6). Alternatively, the radial distance from the test vent to the furthest observation vent can be used as the radius of influence. Generally, it takes a few hours to a few days for vacuums to stabilize at the limits of the area of 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.
- 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
- Turn off the blower and record the recovery in the observation and test vents.

(4) The success of any constant-rate performance test will largely depend on the distribution of the observation vents with respect to the test vents. Therefore, vacuums should be monitored at the observation vents during the stepped-rate tests (see paragraph 4-5*e*) to determine whether additional observation vents are required to establish the area of influence for the constant-rate tests.

(5) Vent efficiency is defined as

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

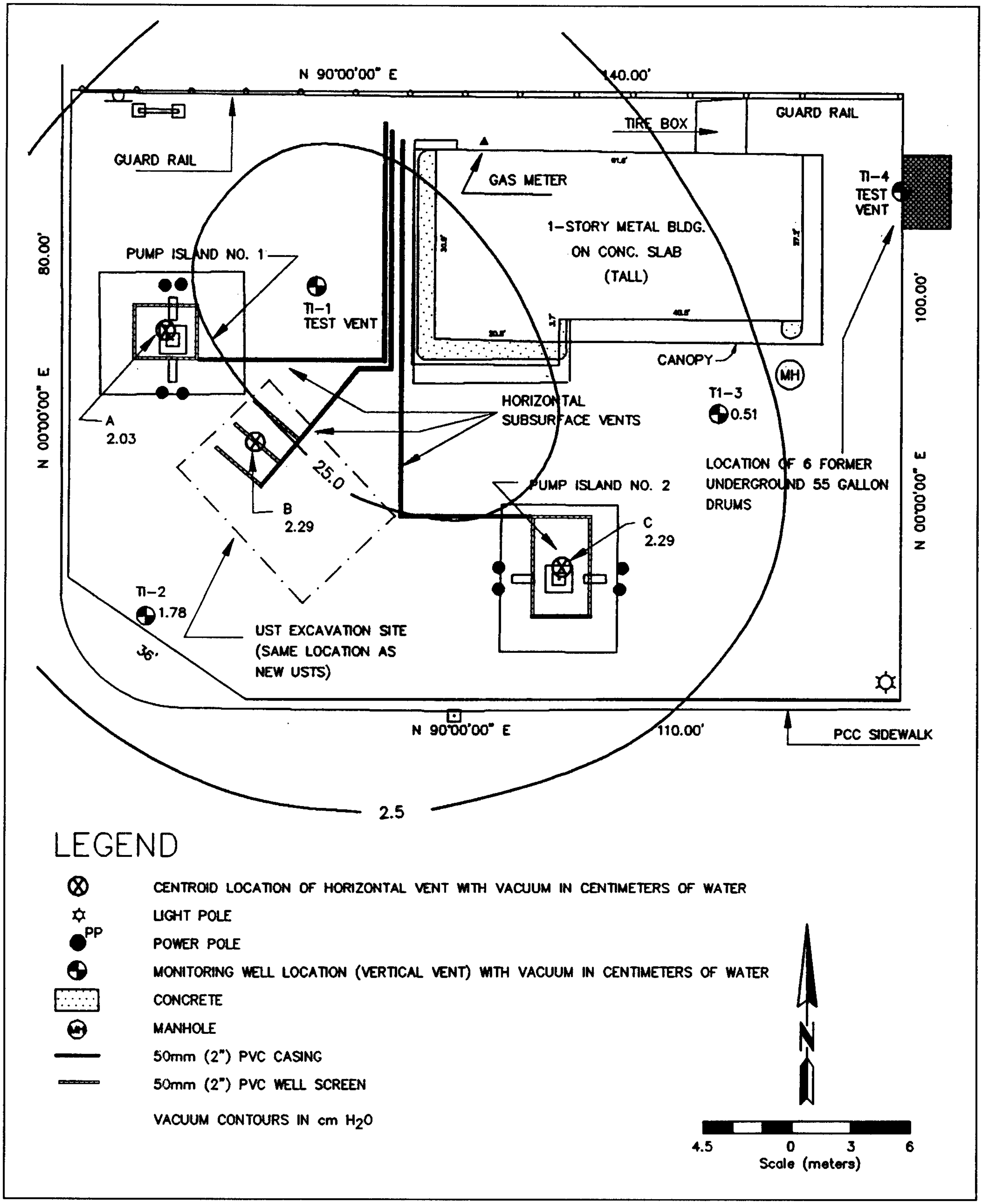


Figure 4-12. Example vacuum map for constant-rate test, vertical vent

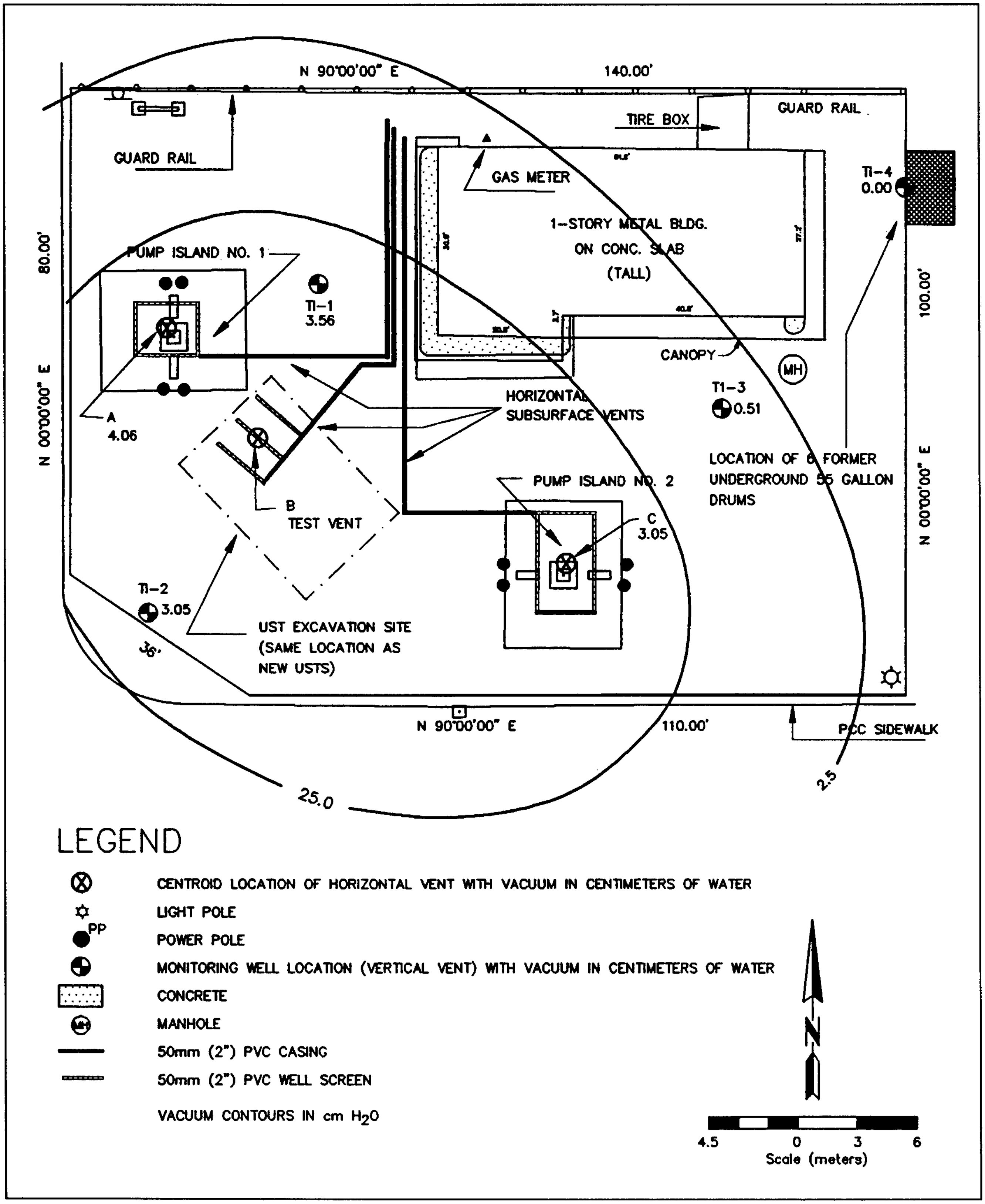


Figure 4-13. Example vacuum map for constant-rate test, horizontal vent

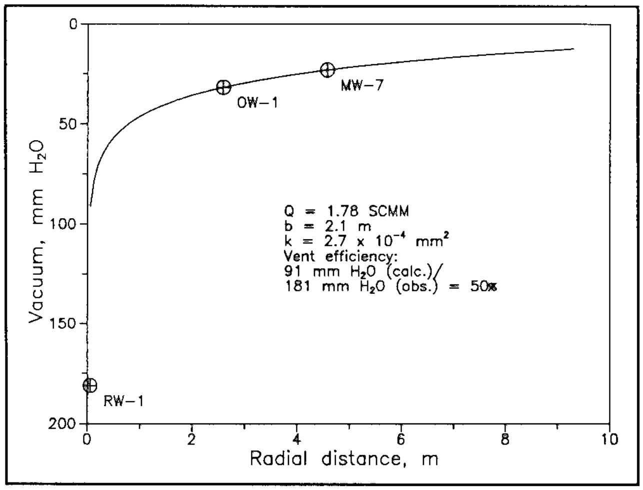


Figure 4-14. Steady-state pump test

where

E = efficiency (dimensionless)

V_{ro} = vacuum just outside the test vent (at radial distance $\sim r_o \approx R_w$) in centimeters of water (or other gauge)

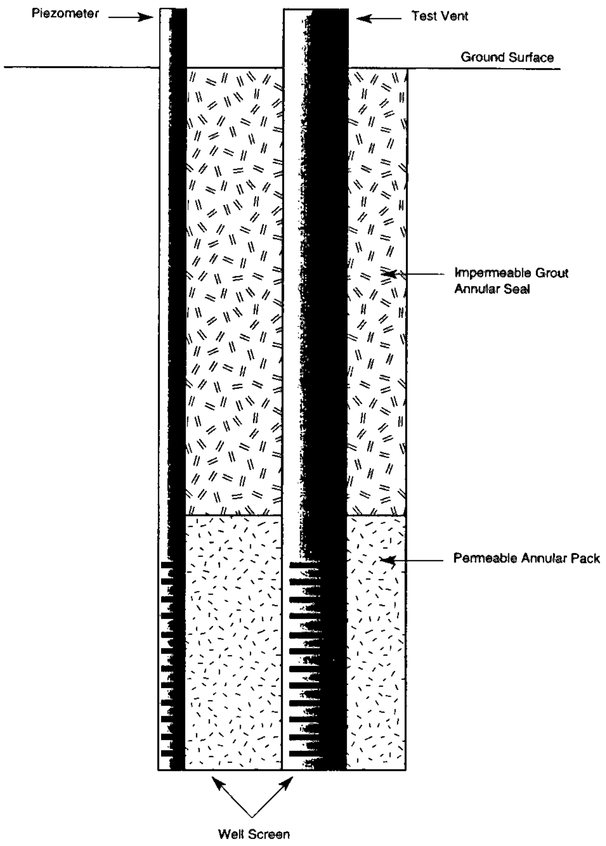
V_w = measured vacuum at the test well head in centimeters of water (or other gauge)

(6) 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. Vent efficiency in SVE/BV is analogous to water well efficiency.

(7) 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 (Figure 4-15).
- Installing observation vents directly adjacent to the vertical or horizontal vent (within a few centimeters of the annulus).

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



Test vent efficiency can be measured directly by taking the ratio of the vacuum observed in the piezometer to the vacuum measured within the test vent.

Figure 4-15. Test vent

(9) 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.

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

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

where

P_{wp} = predicted absolute pressure at the test vent (g/cm·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 (cm)

P_A = absolute atmospheric pressure (~1.01 × 10^6 g/cm·sec^2)

(11) 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, 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:

$$P_{wp} = \left[\frac{\ln(r_2/R_w)\ P_{r\,1}^{\ 2} - \ln(r_1/R_w) P_{r\,2}^{\ 2}}{\ln(r_2/r_1)} \right]^{1/2} \qquad (4\text{-}8)$$

where

P_{wP} = predicted absolute pressure at test vent (distance R_I, g/cm·sec^2)

P_{r1} = absolute pressure at observation vent 1 (g/cm·sec^2)

P_{r2} = absolute pressure at observation vent 2 (g/cm·sec ^{2})

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 of the flow models and to aid in interpreting the data.

(16) For example, the radius of pressure influence for a vertical vent in soil can be estimated using the radial steady-state relationship

$$R_I = R_w \exp \left[\frac{P_A^2 - P_w^2}{P_r^2 - P_w^2} \ln(r/R_w) \right] \qquad (4\text{-}9)$$

where

R_I = radius of pressure influence of the test vent (cm)

R_w = radius of the test vent (cm)

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

P_w = absolute pressure at the test vent (g/cm·sec^2)

P_r = absolute pressure at radial distance r (cm) from the test vent (g/cm·sec^2)

r = radial distance (cm) of the observation vent from the test vent

(17) The calculated R_I is very sensitive to P_w and it is advisable to use the estimated P_{wp} from Equation 4-7 or 4-8 or absolute pressure measured directly adjacent to the test vent as P_w in Equation 4-9 to obtain an accurate estimate of R_I. As in water well testing, it is not advisable to use the producing vent (well) as an observation vent (well) due to head losses between the soil (aquifer) and the producing vent (well).

(18) 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.

(19) 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_I is included in the boundary conditions for 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 Peargin 1991).

(20) Given that vacuum is independent of permeability, arbitrary definitions of radius of pressure influence based on vacuum or pressure head are not necessarily an indicator of capture zone. More importantly, the theoretical radius of 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 which 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 4-16. Measurable vacuum does not imply velocities high enough to accomplish remediation in a timely fashion.

(21) 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

$$q_s = \frac{k_a dP}{\mu n_a ds} \tag{4-10}$$

where

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

(22) 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 simple

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

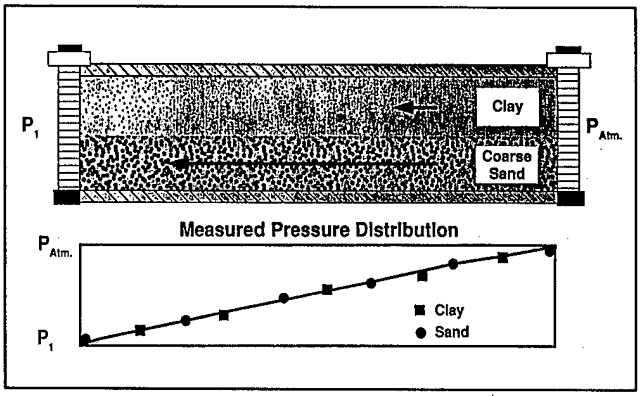


Figure 4-16. Steady-state pressure distribution for 1-D flow between parallel trenches installed in confined layers. Lengths of horizontal arrows indicate relative air velocity. Note that measurable pressure/vacuum readings are no guarantee of significant vapor flow (after Johnson and Ettinger 1994)

where

t = travel time

r = radial distance

(23) 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.

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

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

IV. Results and Discussion

A. Physical Parameters

1. Air Permeability

2. Radius of Influence*

3. Vacuum/Flow Rate Correlation

B. Chemical Parameters

1. Extracted Soil Vapor

2. Treated Soil Vapor

3. Residual Soil

4. 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 4-2*a*).

(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. 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_2O. Table 4-3 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 4-17 presents a plot of the PCE concentrations over time.

(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 4-17. 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

Table 4-3
Column Test Data

Soil Sample

Mass (g)	Area (cm^2)	Height (cm)	Density (g/cm^3)	Temp (°C)
2340	45.6	30.5	1.67	18.20

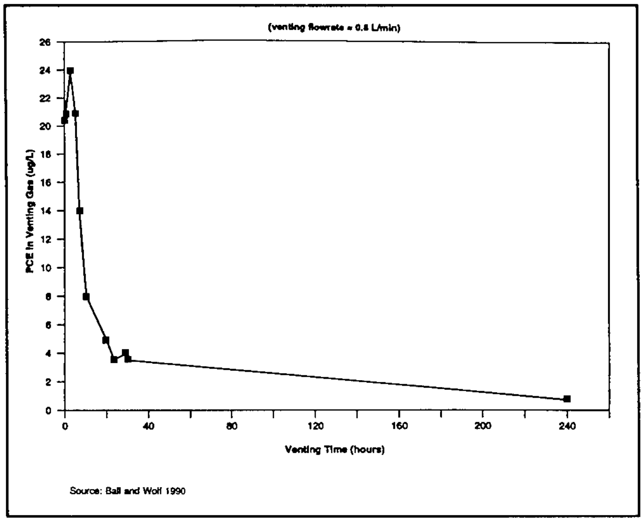
Test Conditions

Airflow Rate (cm^3/min)	Air Loading Rate (cm^3/cm^2-min)	Inlet Pressure (cm H_2O)	Outlet Pressure (cm H_2O)	Pressure Drop (cm H_2O)
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

	EPA Method 5030/8240	
Integration of Figure 4-17 (ppm)	Initial (ppm)	Final (ppm)
13.0	0.500	0.070



Source: Ball and Wolf 1990

Figure 4-17. Tetrachloroethene (PCE) venting curve

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 4-17 shows an average exhaust vapor concentration 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 4-17 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.

(c) Figure 4-17 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).

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 et al. 1992). 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 4-18. 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 by numerically fitting a line to the semi-log plot of the data and solving these equations. The air permeability estimates from the HyperVentilate analysis are provided below:

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

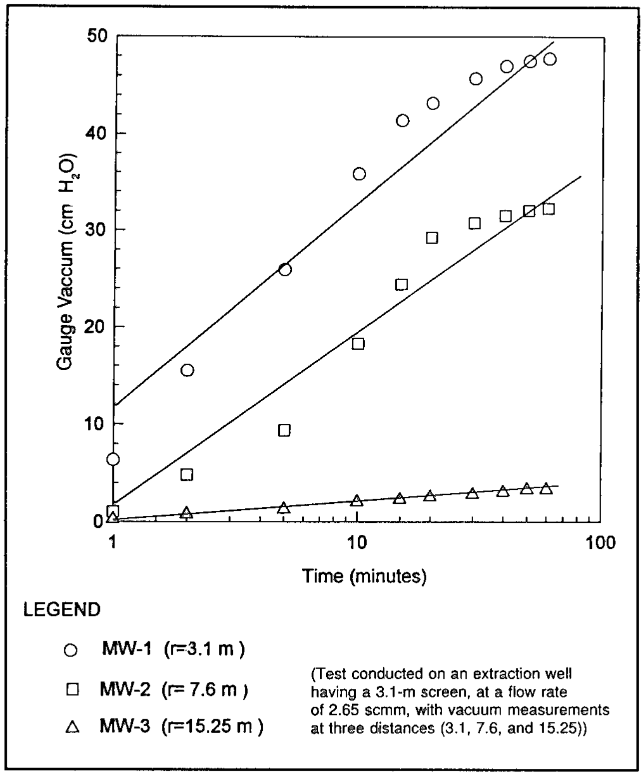


Figure 4-18. Semi-log plot of vacuum versus time for air permeability test

(2) Upon inspection of Figure 4-18, 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 4-5*f*).

(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 4-4 presents the data. Figure 4-19 shows 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 4-20 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.

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 4-2*d*).

Table 4-4
Step Test Data

Vacuum at Wellhead,Vw (mmHg)	Extraction Rate, Q (scmm)	Specific Capacity, Vw (scmm/mmHg)	Vacuum at R = 3.05m (cm. H_2O)	Vacuum at R = 6.10m (cm. H_2O)	Vacuum at R = 12.20m (cm. H_2O)
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

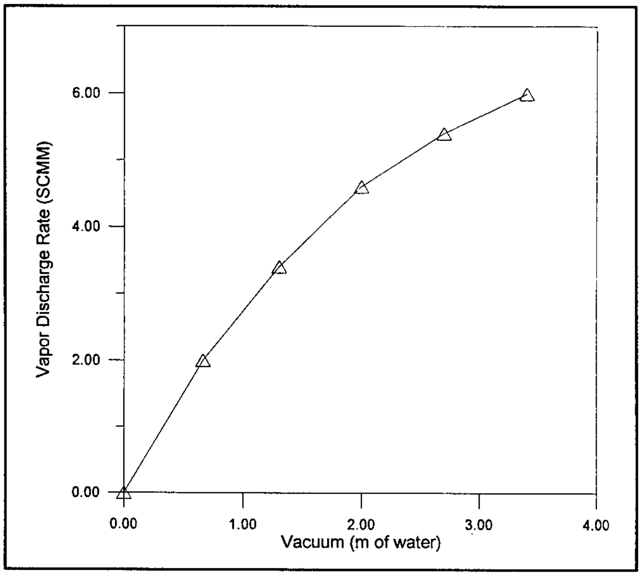


Figure 4-19. Extraction rate versus vacuum

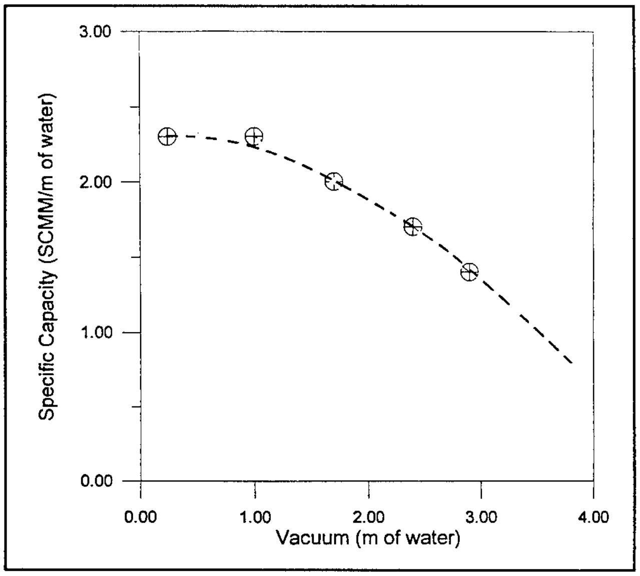


Figure 4-20. Specific capacity versus vacuum

(1) The test consists of injecting air and an inert tracer gas 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 diffusion of oxygen from the ground surface and the surrounding soil and assures 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_2 over time. Table 4-5 and Figure 4-21 show the tabular and graphic forms of the data, which showed an oxygen utilization rate of -0.23 percent per day. The straight-line reduction in O_2 concentration is a typical result.

Table 4-5
Respiration Test Sample Data

Time (hr)	O_2 (%)	CO_2 (%)
-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 site conditions prior to air injection.
** Time = 0 indicates shutdown of air injection.

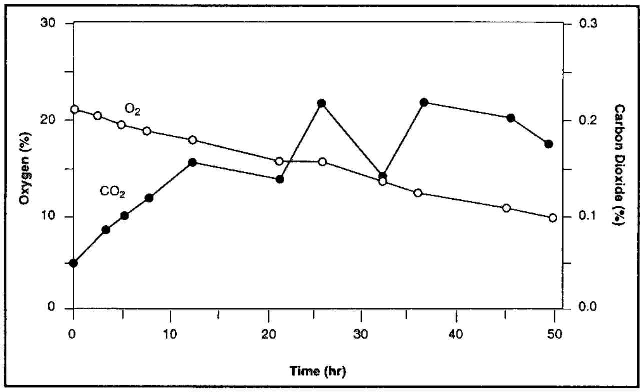


Figure 4-21. O_2 and CO_2 percentages versus time during in situ respirometry test

(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:

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O \qquad (4\text{-}12)$$

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

$$K_B = -K_oAD_oC/100 \qquad (4\text{-}13)$$

where

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

K_o = oxygen utilization rate (percent per day)

A = volume of air per mass of soil (l/kg)

D_o = density of oxygen gas (mg/l)

C = stoichiometric mass ratio of hydrocarbon to oxygen

(d) The following assumptions were made regarding the parameters A, D_o, and C:

- Soil porosity = 0.3
- Soil bulk density = 1,440 kg/m^3
- Therefore, A = (0.3)(1,000 l/m^3)/(1,440 kg/m^3) = 0.21
- D_o = 1,330 mg/l at standard temperature and pressure
- One mole of hexane (0.086 kg) requires 9.5 moles of O_2 (0.304 kg) to completely oxidize it to CO_2 and water, for a mass ratio, C, of 1:3.5

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

$$K_B = -(0.23)(0.21\ l/kg)(1{,}330\ mg\ O_2/l)$$
$$(1\ mg\ C_6H_{14}/3.5\ mgO_2)/100$$
$$= 0.184\ mg \text{ hexane per } kg \text{ soil per day}$$

4-8. Field Criteria for Estimating SVE Feasibility

Recently, 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 4-22a).

(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 4-22 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 pass/fail vacuum of 0.254 cm (0.1 in.) H_2O is applied as a secondary criteria to determine SVE feasibility, because smaller vacuum values are expected to yield low airflow velocities, 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. Values falling within zone 1 of Figure 4-22a 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 4-22b, and the 3 failing tests shown in Figure 4-22c. Similarly, data from 9 pilot tests conducted in low permeability settings are also presented, with the 2 passing tests shown in Figure 4-22d, and the 7 failing tests shown in Figure 4-22e. 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.

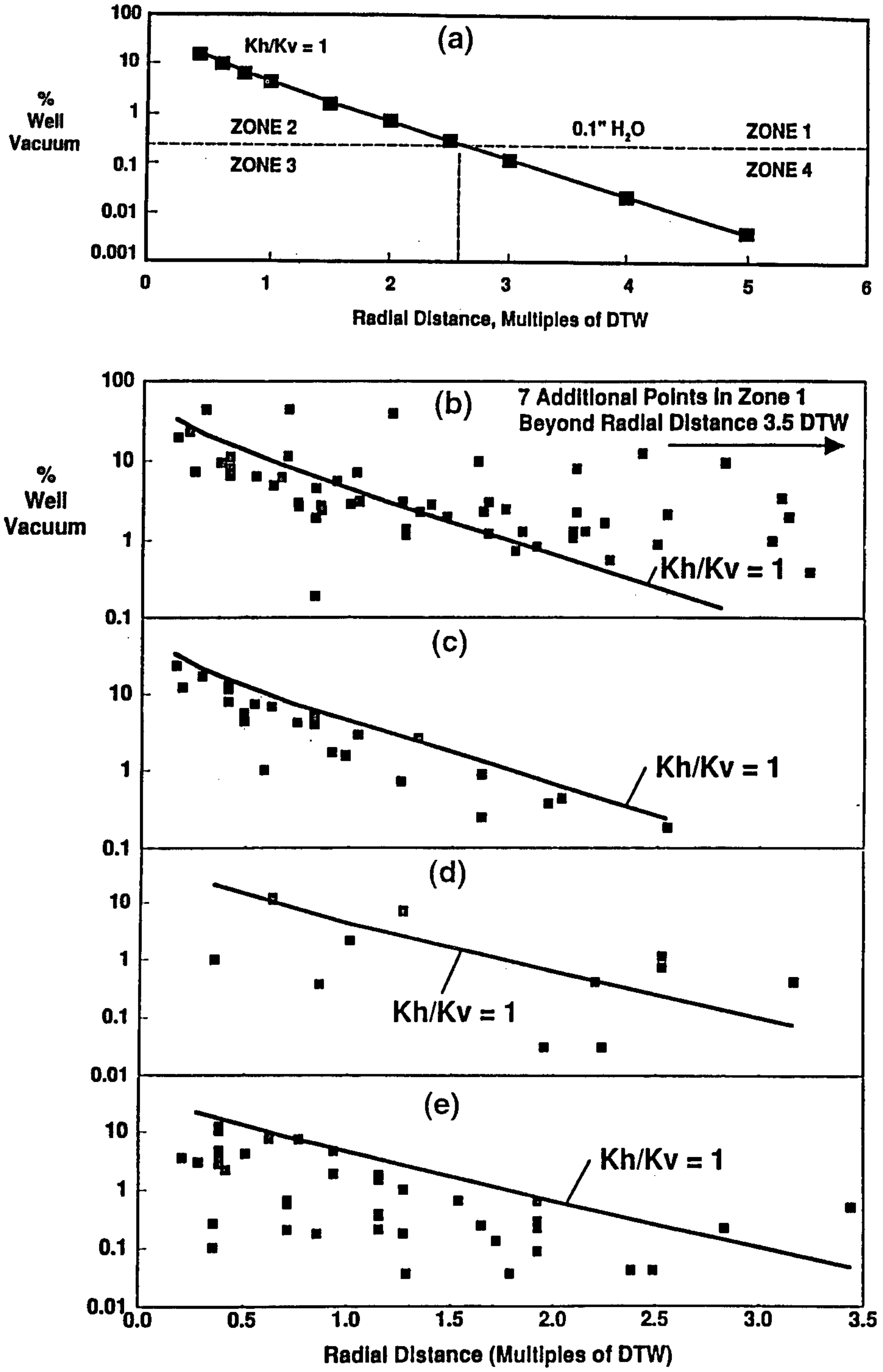


Figure 4-22. Field criteria for estimating venting feasibility, and evaluation of data from 22 pilot tests. (a) Vacuum distribution zones for pass/fail criteria; (b) High K sites passing field criteria; (c) High K sites failing field criteria; (d) Low K sites passing field criteria; (e) Low K sites failing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

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.

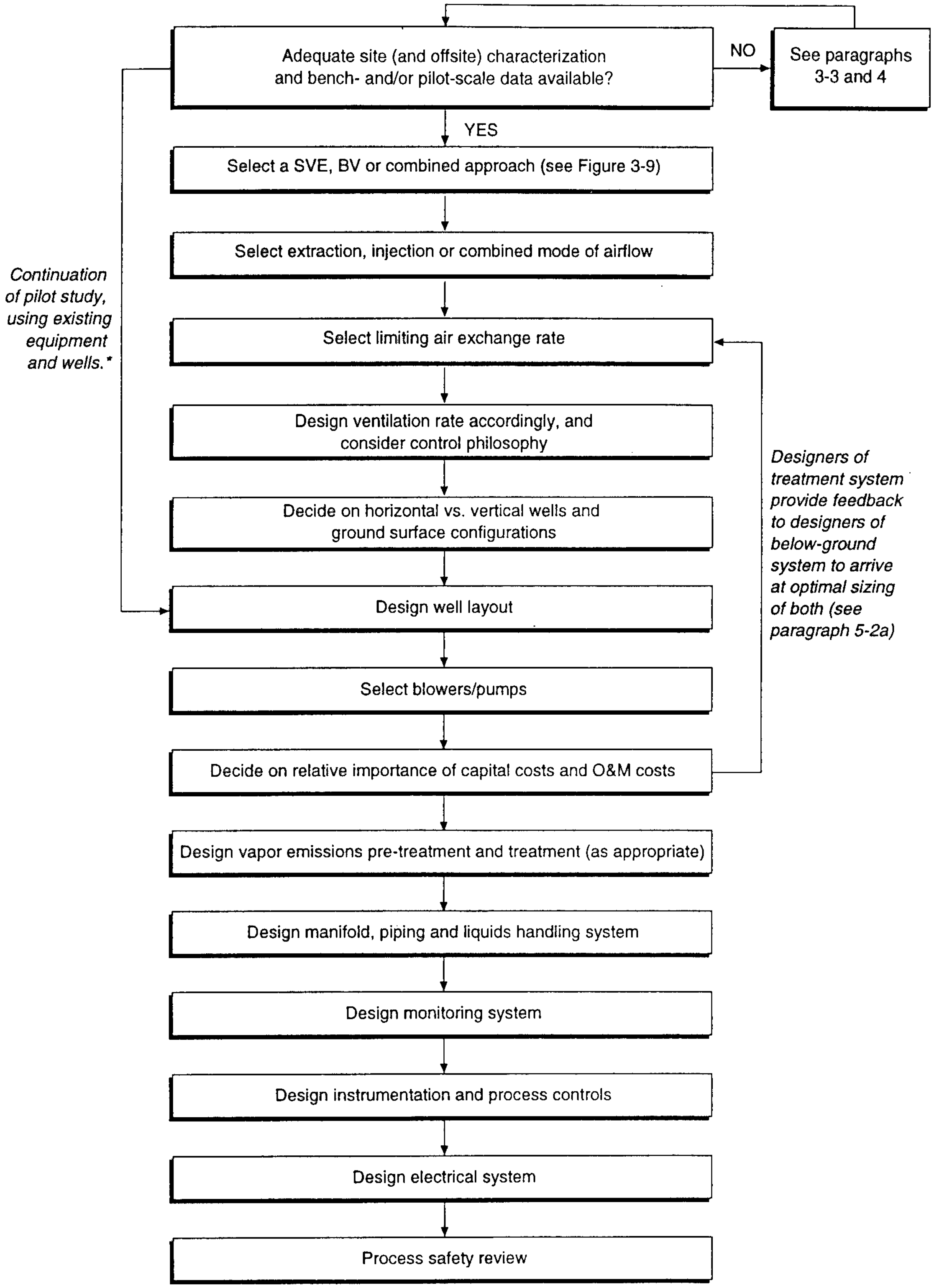
a. Subsurface strategy. The key to a design strategy for SVE and BV systems starts with the recognition that the materials which can be removed from the subsurface with these systems are situated predominantly in the unsaturated zone and in the vicinity of the water table. The release mechanisms for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

(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 3-2.

(2) The primary design parameter is the air permeability of the soil, which is used in determining the radius of influence of 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 provide sufficient oxygen to stimulate microbial activity. 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. Figure 5-1 illustrates the steps that are recommended to properly design a SVE or BV system.

(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 clean the soil air



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

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

very quickly; but over time, due to diffusion or other constraints, the rate at which volatiles are removed from the subsurface becomes increasingly independent of advection and increasingly dependent on diffusion, desorption, and other transport processes (paragraph 2-3*a*).

(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 4-5*f* (20) to (23). 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. The higher numbers are likely intended to accommodate mass transfer limitations (e.g., desorption; dissolution due to high NAPL surface-to-volume ratio; diffusion due to poorly distributed airflow pathways) that will cause the remediation to take longer than otherwise. 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. For BV, recommended pore volume exchange rates to meet microbial oxygen demand range from 1/4 to 1/2 d^{-1}. 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.

(6) 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.

(7) 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.

(8) 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 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.

(9) Finally, the total time for remediation can be calculated by integrating the estimated contaminant removal rate over time. 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.

(10) Stepped flow reductions. Maintaining the initial extraction rate site-wide over the life of the system would be inefficient because a blower and treatment unit sized for the initial high vapor concentrations would quickly become oversized relative to declining contaminant concentrations extracted. Therefore, in order to minimize costs associated with vapor extraction and treatment, it is usually preferable to decrease the extraction rate in steps over the course of remediation. The effect of this tactic is shown in Figure 5-3, which relates cost per kilogram of VOC removed as a function of time for a family of flow

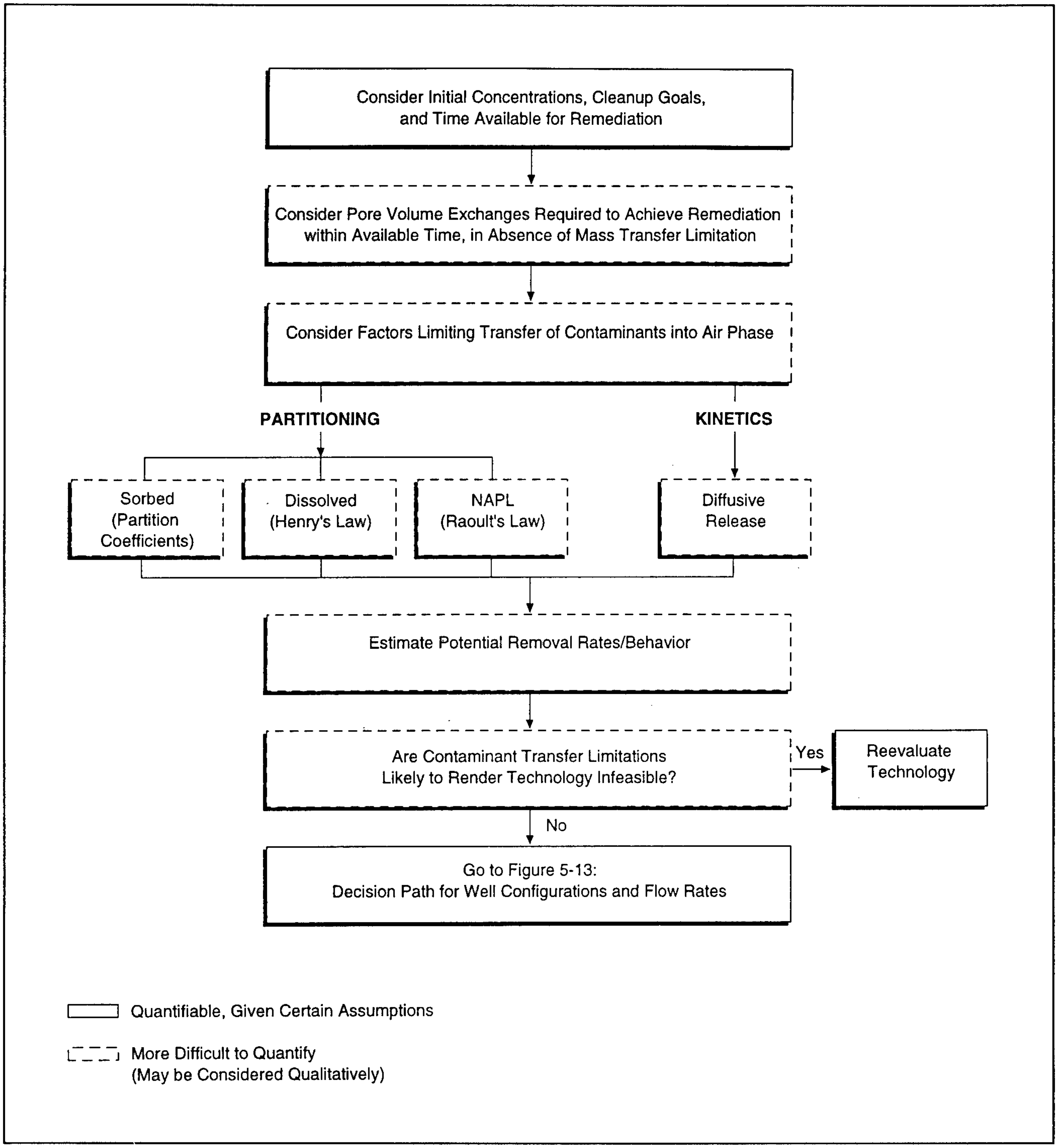


Figure 5-2. Considerations prior to well layout/airflow design

rates. Figure 5-3 implies an infinite family of curves of contaminant removal O&M costs over time. Ideally, one might continuously reduce the flow rate in order to maintain the minimum cost per kilogram at any point in time. Due to intensive labor and management requirements, such continual readjustments are not cost-effective. As a result, a sort of "in-between" methodology is recommended, in which flow rates are reduced step-wise following discrete periods of time. Figure 5-4 shows the

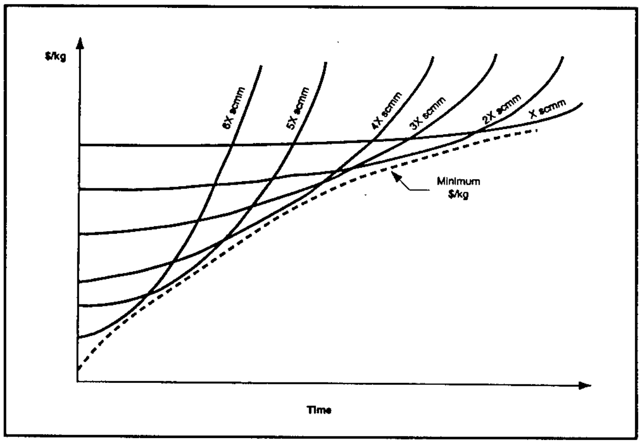


Figure 5-3. O&M cost per kilogram of contaminant removed versus time

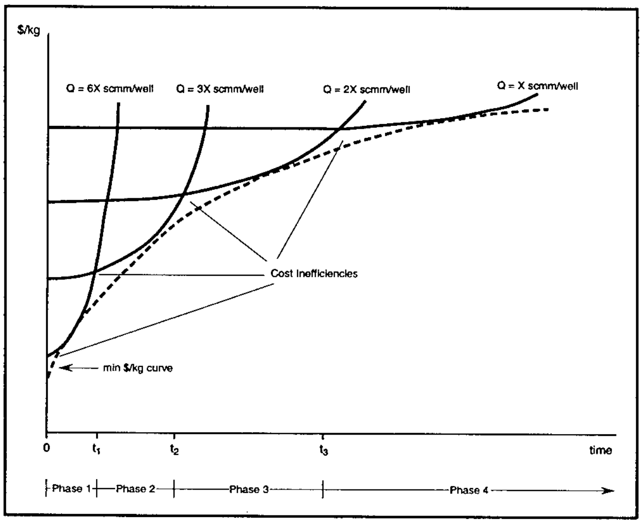


Figure 5-4. Cost effects of stepped flow reductions

slight cost inefficiencies of this method as compared to the ideal, continuous reduction scenario.

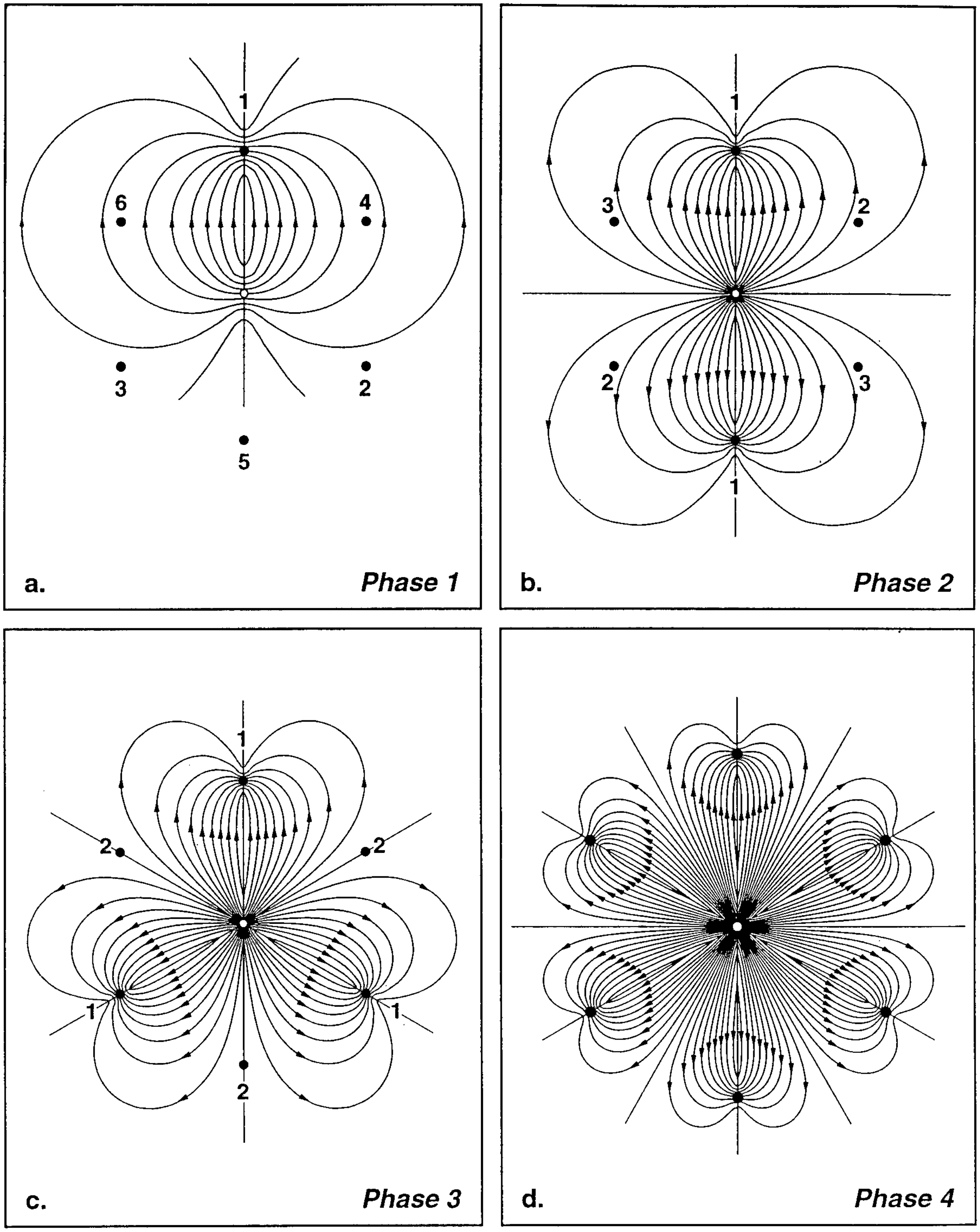
(11) The cost inefficiencies shown in Figure 5-4 can be reduced by including additional flow adjustments. However, the marginal increases in savings associated with an additional flow adjustment will sharply diminish for each additional adjustment, while the labor and management costs remain essentially the same. Clearly, there is an optimum number of flow adjustments that will minimize the cost of contaminant removal throughout the remediation. Based on site specifics, it is estimated that, over the course of a 2-year remediation effort, a range of two to four flow adjustments may be called for. As indicated in Figure 5-4, most of the adjustments would be needed in the early stages of operation due to the flattening of the minimum cost curve. This is expected because of the fairly rapid decline of VOC concentrations in the early stages followed by relatively constant concentrations later in the remediation as diffusion processes begin to limit the removal rates.

(12) As an additional boost to maximizing removal efficiency in conjunction with the methods described above, it is recommended that, in multiple well scenarios, the extraction wells be rotated initially (i.e., during the phases with the highest flow rates). In such a scenario, a single blower could be used during the entire process. Consider a hypothetical array of six vapor extraction wells around a single air injection well (Figure 5-5). In Phases 1 through 4 which follow, the air injection well is operated at a constant rate of Q = 6x scmm. Conceptually, the extraction would begin (Phase 1) with the blower extracting vapor at a rate of 6x scmm from one extraction well at a time (Figure 5-5a), cycling through the six extraction wells in sequence over the course of, say, a day. Phase 1 would continue until the extracted VOC concentrations were a certain percentage of the initial levels (e.g., 20 to 30 percent, depending on site and contaminant specifics).

(13) In Phase 2 (Figure 5-5b), the blower would be manifolded to two of the six wells and operated at the same total flow rate, but with only roughly half of the flow (3x scmm) (depending on the degree of homogeneity at the site) coming from any single well. This will increase the contaminant loading (i.e., the amount of VOCs in a cubic meter of extracted vapor) over that which was seen at the end of Phase 1. As with Phase 1, however, VOC concentrations will also diminish, albeit at a slower rate. Rotation among the well pairs will be necessary each day.

(14) Phase 3 (Figure 5-5c) will be much like Phase 2, except that the blower will now be manifolded to three wells rather than two, and the appropriate reduction in extraction rates per well (2x scmm) will be maintained, although the total rate should remain relatively constant. Extraction will alternate between the two sets of triplets daily. Contaminant loadings should be expected to decrease even more slowly than in Phase 2.

(15) Finally, Phase 4 will consist of manifolding the blower to all six wells and extracting simultaneously from each one at a rate of × scmm, one-sixth of the initial, maximum rate applied to each well in Phase 1. By this time, diffusion kinetics should be the limiting removal mechanism, and contaminant loadings should remain in a quasi-steady state while slowly decreasing during the remainder of operation. As an additional variation, air



Closed circles are vapor extraction wells; open circles are air injection wells.

Figure 5-5. Stepped flow reductions example plan view showing predicted airflow streamlines

could be injected into one or more of the wells previously used for extraction, and vice versa. There are a number of benefits accruing from a stepped flow reduction operational strategy. In large multiwell systems, specification at the outset of smaller blowers and off-gas treatment systems can substantially reduce capital costs. In addition, operating horsepower may be only 1/3 of what it would be if all wells were operating simultaneously, reducing electrical costs accordingly. A further benefit is that the changing flowlines avoid creation of stagnation zones and help to ensure that airflow occurs via as many subsurface pathways as possible, thereby shortening diffusion pathlengths and accelerating the overall cleanup.

(16) Mass removal rates can be calculated from vapor concentrations and flow rates using the equation presented in Table 7-1.

(17) It should be noted that Figure 5-3 reflects only the costs to run the blower and treatment systems, and does not reflect the costs for additional wells that may be required to provide site coverage at lower flow rates (see paragraph 5-3).

(18) It should also be noted that, as discussed in paragraph 4-5*f*, reducing the flow rates will reduce the radius of influence of a given well. As a result, well spacings should be set based on the anticipated zone of effective air exchange under the long-term, equilibrium flow rate. This, of course, will entail overlapping such zones during the initial stages of extraction, when flow rates are high. Stagnation within these overlapping zones will not occur when flows are cycled among wells. When multiple wells are operating simultaneously, stagnation zones can be precluded by installing active air injection wells (paragraph 5-3*c*), or by varying flow rates among the wells.

(19) Likewise, 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. 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.

(20) In cases where a combined SVE/BV approach will be applied, 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, microbial population counts, pH, moisture, nutrient concentrations, temperature, and vapor phase contaminant emissions at the ground surface.
- The possible need for additional wells due to the fact that with lower airflow rates, radii of influence will be smaller. To some extent, this will be compensated for because during BV, lower pore volume exchange rates and hence lower velocities are apt to be sufficient than during SVE. Consequently, the definition of an acceptable radius of influence may change over the life of a project.

b. Overall pneumatic considerations. 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.

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 level applied.

(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-Weisback equation:

$$h_f = (fL/d)\ (v^2/2g) \qquad (5\text{-}1)$$

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 which 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 5-6 is a friction loss chart that has been developed for inlet air at 294 °K 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 5-7. 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 multiwell 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 5-7. The designer must verify that the new flow rate and pressure are within the operating range of the blower.

(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.

c. *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

This chart may be used to compute friction losses in a piping system. For example, determine the friction loss incurred when 70 CFM flows through a 2" pipe, 50' long.

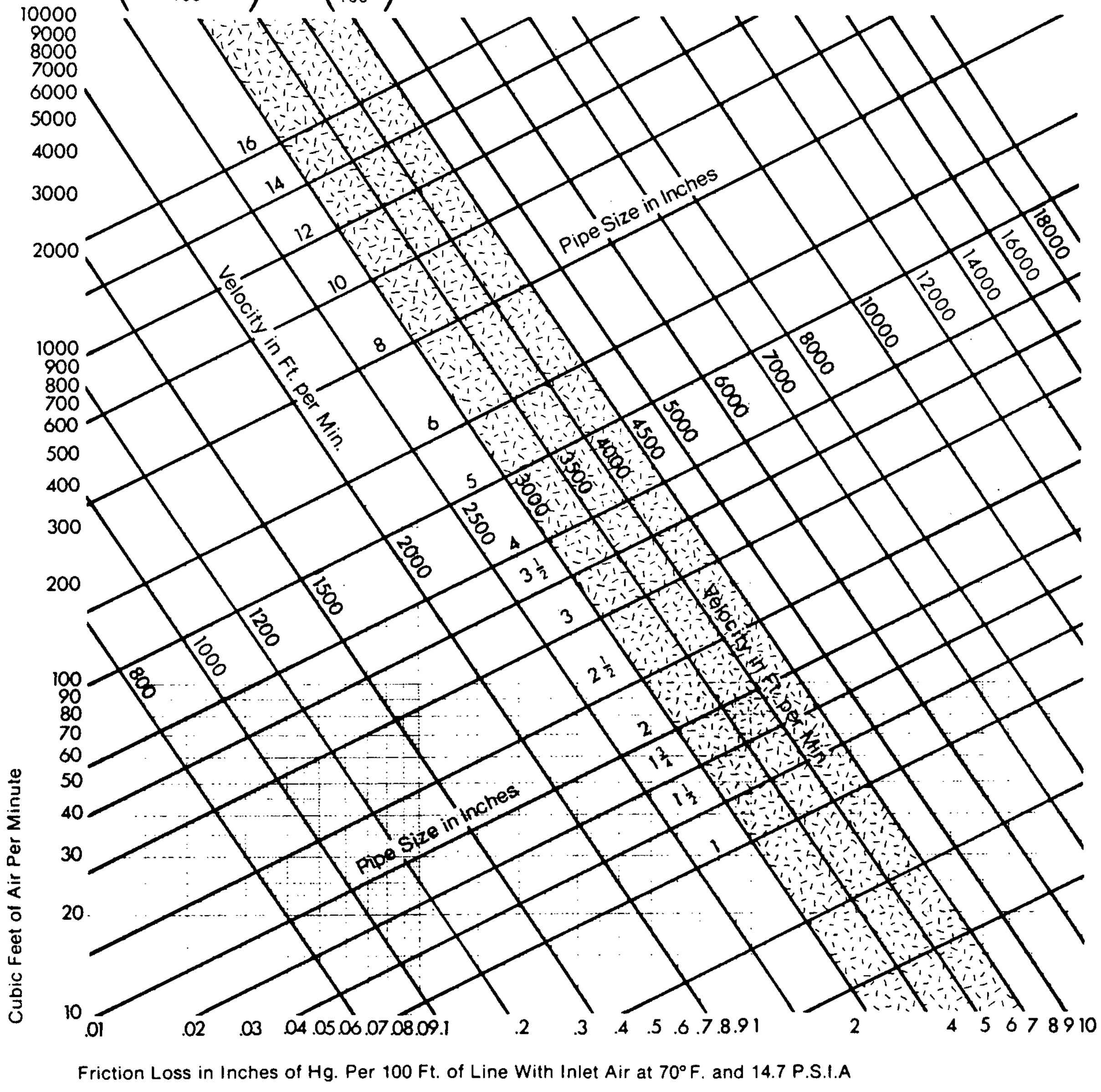
Step 1: Intersect 70 CFM and the sloping line for 2" pipe as shown.

Step 2: Drop a vertical from this point of intersection and read the loss/100' of line, in this case, .60Hg/100'.

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

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

Also: Velocity in the line may be read from the negatively sloping lines on the graph. Here, to get 70 CFM through a 2" line, the air must travel at a velocity of approximately 3000 FPM.



Source: Spencer Turbine Co. 1987

Figure 5-6. Friction loss chart

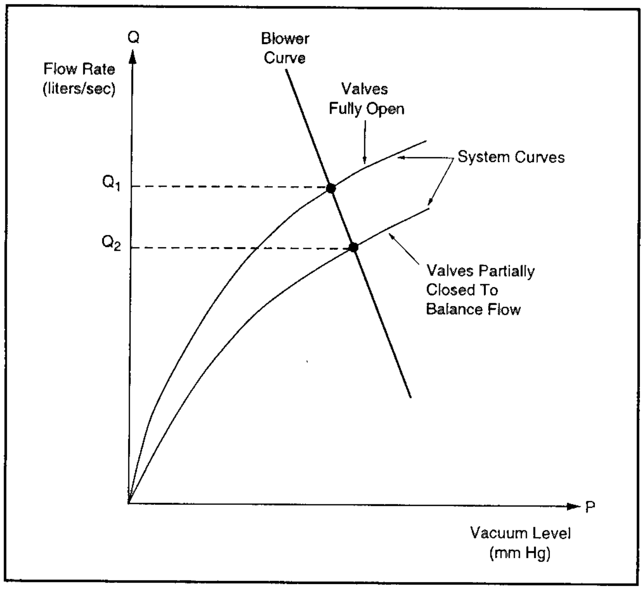


Figure 5-7. Typical SVE pneumatic analysis

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:

$$h = aQ \tag{5-2}$$

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 5-8) 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.

(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, Q4, and the flow in pipelines Q1 and Q2 are assumed. The flow in the last line is determined by continuity,

$$Q3 = Q4 - Q1 - Q2 \tag{5-3}$$

(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, ε/D, was based on smooth steel pipe. The friction factor calculation was based on the Sacham equation:

$$f = \{-2 \log [(\varepsilon/D)/3.7) - (5.02/Re)\cdot\log [(\varepsilon/D)/3.7 + (14.5/Re)]]\}^{-2} \tag{5-4}$$

(5) Although Equation 5-4 is not as accurate as the Colebrook equation, it is an explicit expression which greatly simplifies the calculation. The Sacham equation was checked against a Moody Friction Factor chart to assure accuracy.

(6) 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.

$$L_{total} = L + \sum n\cdot L_e \tag{5-5}$$

where

n = the quantity of each fitting

L_e = the equivalent length

(7) The friction loss for an individual pipeline was calculated based on the Darcy-Weisback equation (Equation 5-1). 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.

(8) An iterative calculation was performed to develop the system curve. Notice from Figure 5-8 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 (h1

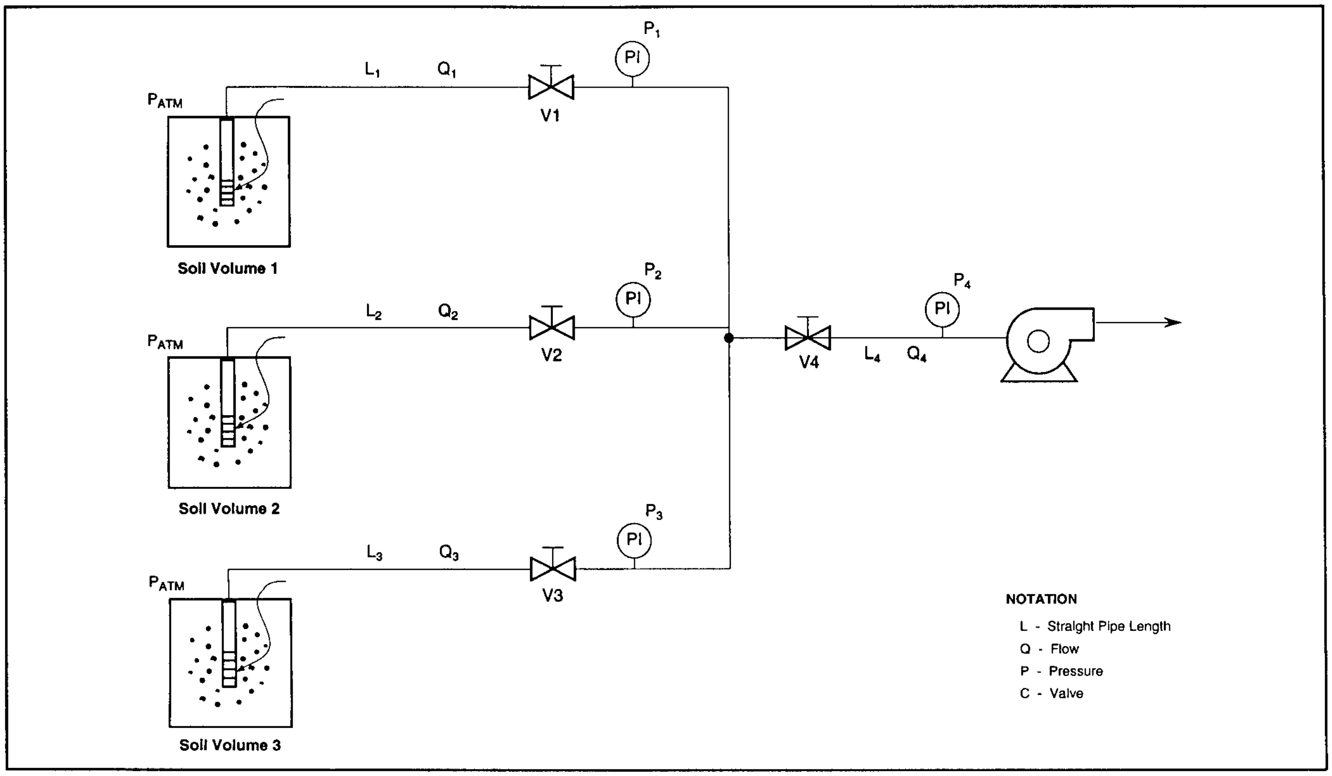


Figure 5-8. Piping network for pneumatic calculation

or h2 or h3) was added to the frictional loss in the combined line (h4) to get the total frictional loss. The results were tabulated (Table 5-1b) and the data were plotted in Figure 5-9. A blower curve was selected to match the system curve.

(9) 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 19.59 mmHg are lost through line 4, lines 1 through 3 must all induce a loss of the remaining 64.71 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, 8.85 and 19.2 mmHg are subtracted from a total of 64.71 mmHg to obtain 36.66 mmHg. This analysis demonstrated that it is possible to achieve 64 L/s at each well.

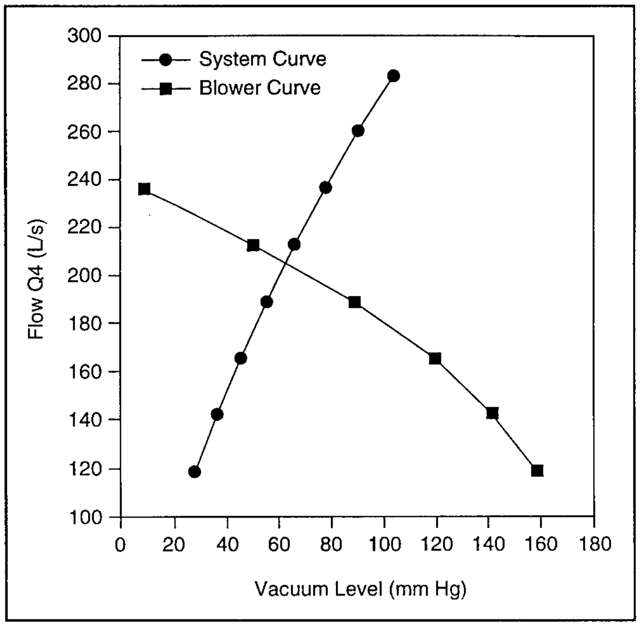


Figure 5-9. Results of pneumatic analysis

Table 5-1a
Pneumatic Analysis for SVE System: Calculation Spreadsheet for a Single Point (Continued)

Constants					
Density =	1.293 kg/m^3		(at 0 deg C)		
Viscosity =	1.71E-05 (kg/m*s)		(at 0 deg C)		
Gravity (g)	9.81 m/s^2				
	LINE 1	**LINE 2**	**LINE 3**	**LINE 4**	**COMMENTS**
Flow (L/s)	78.83	65.39	44.54	188.76	Q3 = Q4 - Q2 - Q1
Flow (M^3/s)	0.07883	0.06539	0.04454	0.18876	
Nom. Dia. (in)	3	3	3	4	Given
D [m]	0.0777	0.0777	0.0777	0.1020	Pipe ID (sch. 40)
Int. Area (m^2)	0.0047	0.0047	0.0047	0.0081	Pipe area
Vel. (v) [m/s]	16.6842	13.8397	9.4268	23.1995	v = (Q/A)
Reynolds #	9.81E+04	8.13E+04	5.54E+04	1.79E+05	Re = D*v*den./visc.
e/D	5.87E-04	5.87E-04	5.87E-04	4.47E-04	Steel pipe roughness
f	0.021	0.021	0.023	0.019	Friction factor
L (m)	100	250	150	50	Straight pipe length
Equivalent Lengths					
90 deg Elbow	2.34	2.34	2.34	3.08	
Tee (str. thru)	1.56	1.56	1.56	2.05	
Tee (Branched)	6.13	6.13	6.13	7.68	
Gate Valve	0.62	0.62	0.62	0.82	Fully opened
	LINE 1	**LINE 2**	**LINE 3**	**LINE 4**	**COMMENTS**
Globe Valve	26.49	26.46	26.49	34.75	Fully opened
Butterfly Valve	3.51	3.51	3.51	4.60	Fully opened
Expansion	1.37	1.37	1.37	1.58	
Contraction	0.49	0.49	0.49	0.82	

Table 5-1a
(Concluded)

Quantities					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	118.8244	271.1622	168.8244	129.4430	L + sum(L*n)
Pressure Head [meters of air]	137.27	220.87	67.75	199.36	$hf=(f*L*v^2)/(2*D*g)$
Pressure Loss [kg/m^2]	177.49	285.58	87.28	257.77	hf * density
Pressure Loss [mmHg)	13.06	21.02	6.42	18.97	kg/m^2 * 0.0736
	LINE 1	**LINE 2**	**LINE 3**	**LINE 4**	**COMMENTS**
Subsurface pneumatic losses					
Regr. Coef. (a)	300	240	680	0	From pilot study (given)
Subsurface Loss [mmHg]	23.649	15.6936	30.2872	0	h = a*Q
Pressure loss induced by closing valves					
Valve Loss	0	0	0	0	
Total Loss [mmHg]	36.71	36.71	36.71	18.97	Surface + subsurface

Table 5-1b
Pneumatic Analysis for SVE System: Tabulated System and Blower Curves

Q1 [L/s]	Q2 [L/s]	Q3 [L/s]	Q4 [L/s]	h1,h2,h3 [mmHg]	h4 [mmHg]	System Curve Total h [mmHg]	Blower Curve [mmHg]
48.94	43.10	25.96	118.00	20.06	7.84	27.90	158.75
58.92	50.69	31.99	141.60	25.26	11.03	36.29	141.94
68.89	58.11	38.20	159.20	30.82	14.74	45.56	119.53
78.83	65.39	44.54	188.76	36.71	18.97	55.68	89.64
88.77	72.59	51.04	212.40	42.97	23.74	66.71	50.43
98.69	79.68	57.63	236.00	49.54	29.01	78.55	9.34
108.52	86.67	64.31	259.50	56.42	34.78	91.20	
118.38	93.61	71.11	283.10	63.66	41.09	104.75	

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)	8.85	20.19	12.57	19.59	
Subsurface Loss (mmHg)	19.20	15.36	43.52	0.00	
Valve Loss (mmHg)	36.66	29.16	8.62		
Total Loss (mmHg)	64.71	64.71	64.71	19.59	84.30
Flow (L/s)	66.0	66.0	66.0	198.0	
Surface Loss (mmHg)	9.37	21.39	13.31	20.77	
Subsurface Loss (mmHg)	19.80	15.84	44.88	0.00	
Valve Loss (mmHg)	24.36	16.30	-4.66	0.00	
Total Loss (mmHg)	53.53	53.53	53.53	20.77	74.3

(10) Now suppose that it is desirable to operate each well at 66 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, 66 L/s cannot be achieved at each well.

(11) 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.

(12) 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 66 L/s at each well. The system would operate at a total flow of 205 L/s (the intersection of the two curves of Figure 5-9) without equalizing the flow. Therefore, roughly 13 L/s would be lost by equalizing the flows to 64 L/s.

(13) 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.

(14) 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.

d. 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.

5-3. 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.

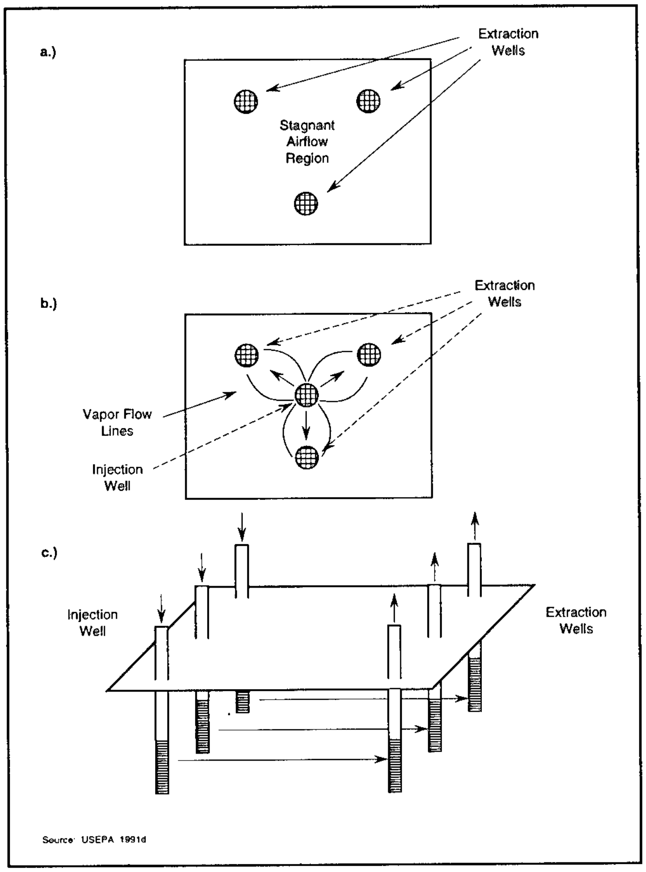
a. Well layout. The primary goal of an SVE or BV system is to cause air transfer within the contaminated zone. For SVE systems, the goal is to provide air throughput at a rate that allows efficient transfer of contaminants but is still fast enough to remediate the soil within a desired time frame. For 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) In the past, designers have often used a "radius of influence" approach to choosing well spacing. The radius of pressure influence (paragraph 4-5*f*) 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 flow rates at the edges of the treatment zone.

(2) A more relevant approach to well layout is to require the initiation of an air 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. Determination of this velocity is, however, problematic. Column studies of contaminant removal versus pore volumes of air passed through the column can give some indication of the amount of air needed to remediate the soil. There are several considerations in applying this analysis, however. The required air throughput is dependent on the initial soil concentrations (lower concentrations would require less air). Also, mass transfer kinetics can affect the efficiency of the removal, particularly where contaminants are only present in dissolved form in soil moisture or in dead-end pores. As previously discussed, optimum air velocities may change over time because of these phenomena and thus well spacing requirements may change over time as well. Note that column test results, because of the relatively high airflow rates, may overestimate the air required to remove contaminants.

(3) Analyses of air velocities and travel times to the extraction wells at various flow rates are 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. Computer models can be used for this analysis.

(4) 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 5-10, 5-11, and 5-12). Computer models can be used to project the effect of passive or active air injection wells.



Source: USEPA 1991d

Figure 5-10. Example venting well configurations

b. Extraction well screen placement.

(1) The main objective in extraction well placement is to induce air to flow through the zone of contamination.

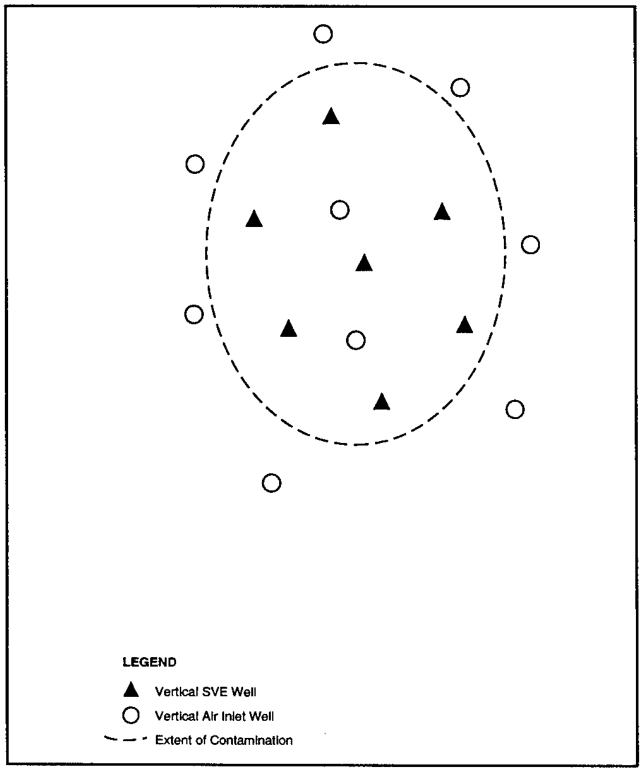


Figure 5-11. Vertical extraction/inlet well layout scheme (asymmetric layout reflects anisotropic conditions at site)

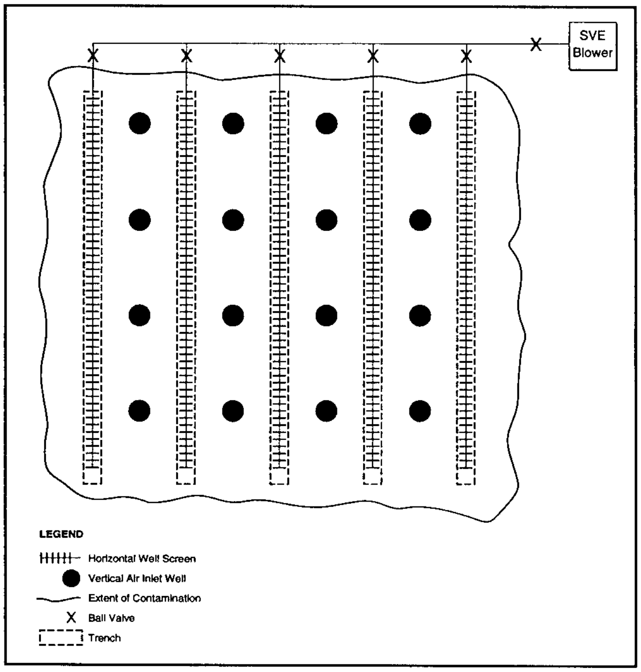


Figure 5-12. Plan view of typical horizontal extraction/ vertical inlet well scheme

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 radius of influence of a given extraction well (Shan, Falta, and Javandel 1992). It is strongly suggested that flow models such as AIRFLOW, AIRTEST, or MODFLOW be used to optimize screen depths. These and other SVE/BV models are described in Appendix C.

(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.

c. *Passive/active injection well placement.*

(1) Both passive and active injection wells can be used to enhance the volatilization of contaminants into the soil air and control the air movement through the contamination zone. Passive inlet wells are open to the atmosphere, allowing air to be drawn into the soil from the lower atmosphere. These wells are typically used to limit the radius of influence of a particular well. An example would be the case where two adjacent properties have volatile contaminants in the subsurface. A passive inlet system installed along the property boundary would allow 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.

(2) Active injection wells use forced air from a blower or compressor to promote the movement of air through the soil. Active injection is typically used to increase pressure gradients, and thus induce higher flow rates, in stagnant areas near the fringe of a well's radius

of influence. Injection wells should be placed so that contamination is directed toward the extraction wells. Although screened intervals vary in length, they should allow for uniform airflow from the injection to the extraction wells. Injection wells are usually installed vertically outside the edge of the contaminated area. A well-designed soil venting system allows vents to act interchangeably as extraction, injection, and/or passive inlet wells.

(3) Inlets or injection wells permit the subsurface airflow to be focused on a specific contaminated interval. This increases the throughput of air in that interval and may ultimately speed remediation. In some cases, inlets or injection wells can reduce treatment time by allowing greater airflow rates than otherwise would be possible. They also permit specific areas to be more heavily treated. They can, for example, promote horizontal airflow through a given stratum. Although more expensive, steam can be injected into the soil instead of air to increase the volatilization of the contaminants.

(4) The disadvantages of installing passive inlet or active injection wells at a site include the added cost associated with the construction of additional wells and the additional energy cost of operating the compressor or blower for active injection wells. The addition of clean air to the subsurface may also dilute vapor phase contaminant concentrations, thereby increasing offgas treatment costs.

(5) Passive/active injection wells are similar in construction to extraction wells (refer to paragraph 5-4), but they often have longer screened intervals. 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 5-13. 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. Streamtube calculations are used to determine the required flow 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.

(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 5-13. 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.

(6) 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.

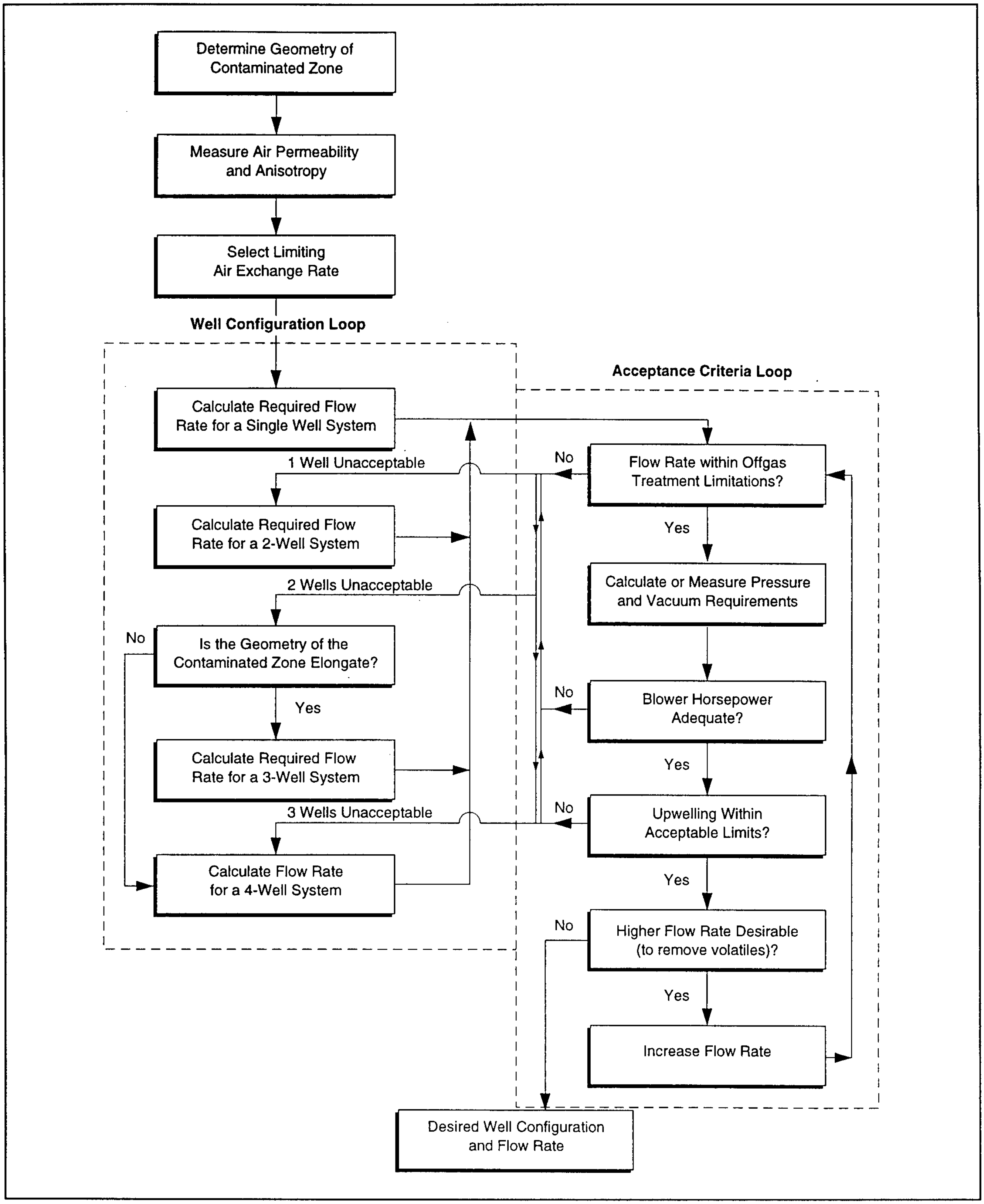


Figure 5-13. Decision path for well configurations and flow rates

(7) Because single well systems generally involve the lowest installation cost, these systems form the first tier of the well configuration loop (Figure 5-13). For sites with impermeable surface covers, the required flow rate for a single well system can be calculated via:

$$Q_v^* = \frac{\pi r^2 b n_a}{t_{xc}} \tag{5-6}$$

where

Q_v^* = volumetric flow rate at amospheric 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_{xc} = the time required for one pore volume exchange [T]

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.

(8) 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:

$$Q_v^* = \frac{2\pi b^2 n_a A (L - l) \tau}{t_{ex}} \tag{5-7}$$

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]

τ = 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. If the maximum extent of contamination occurs near the water table, then dimensionless travel times obtained from Figure 5-14 may be used in Equation 5-7. It should be noted, however, that the dimensionless travel times shown in Figure 5-14 assume that there is no reduction in flow velocity due to increased water saturations near the water table.

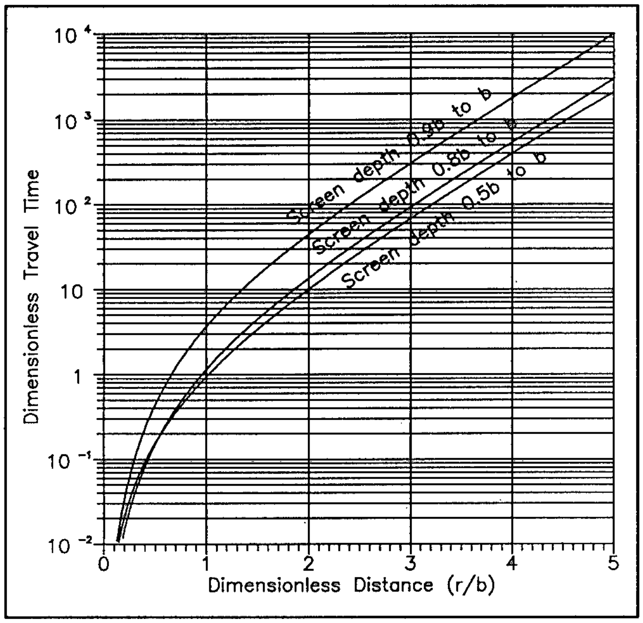


Figure 5-14. Dimensionless travel times at the water table for wells screened within the lower half, fifth, and tenth of the vadose zone (Brailey 1995, unpublished data)

(9) To evaluate the adequacy of a single well system, the flow rate obtained from Equation 5-6 or 5-7 should be compared against the acceptance criteria shown in Figure 5-13. 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.

(10) If the required flow rate for a single well system exceeds the acceptance criteria shown in Figure 5-13, the decision path aborts to evaluation of two-well systems. 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 5-15. Note that in the streamtube plots which follow, each of the streamtubes transmits an equal fraction of the total airflow represented within the drawing.

(11) The flow geometry shown in Figure 5-15 applies where the extraction rate equals the injection rate. As shown in Figure 5-15, 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.

(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 5-15. 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:

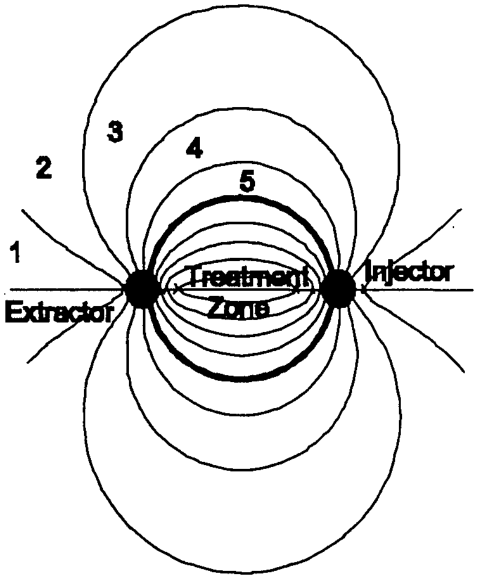
$$t = \frac{V_{\#6}}{\frac{1}{20}Q_v^*} = \frac{0.133 L^2 b n_a}{\frac{1}{20}Q_v^*} = \frac{2.66 L^2 b n_a}{Q_v^*} \qquad (5\text{-}8)$$

where

$V_{\#6}$ = volume of streamtube No. 6 [L^3]

Q_v^* = volumetric flow rate at atmospheric pressure [L^3/T]

L = distance between the two wells [L]



Dimensionless Streamtube Areas (x 10^2)

Tube	Area	Tube	Area
1	∞	6	13.3 L^2
2	603 L^2	7	9.21 L^2
3	115 L^2	8	7.12 L^2
4	42.8 L^2	9	6.65 L^2
5	21.8 L^2	10	4.74 L^2

L = well spacing

Brailey (1995), unpublished data

Figure 5-15. Plan view of streamtubes for a two-well system

To determine the required flow rate, use Equation 5-9 setting the time for one pore volume exchange (t_{ex}) equal to the design criterion:

$$Q = \frac{2.66L^2bn_a}{t_{ex}} \qquad (5\text{-}9)$$

Equation 5-9 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 5-15. 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 5-16. This well spacing represents the maximum spacing that will not cause substantial breakthrough of atmospheric air between the extraction well and the injection well.

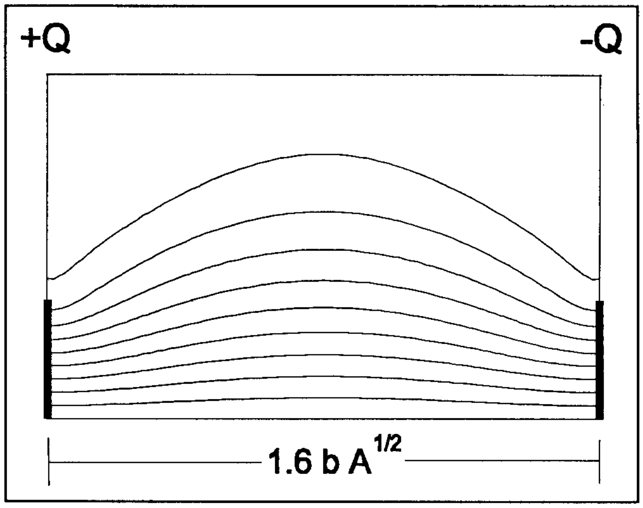


Figure 5-16. Profile of streamtubes for a two-well system

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 5-9 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 5-16.

(16) If an adequate air exchange rate cannot be accomplished with a two-well system, then three- or four-well configurations may be evaluated. If the contaminated zone is elongate in plan view, then a three-well system should be considered. If the contaminated zone is roughly equant in plan view, then a four-well configuration is more appropriate.

(17) As shown by Figure 5-17, three-well systems are best suited for elongate 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 5-17.

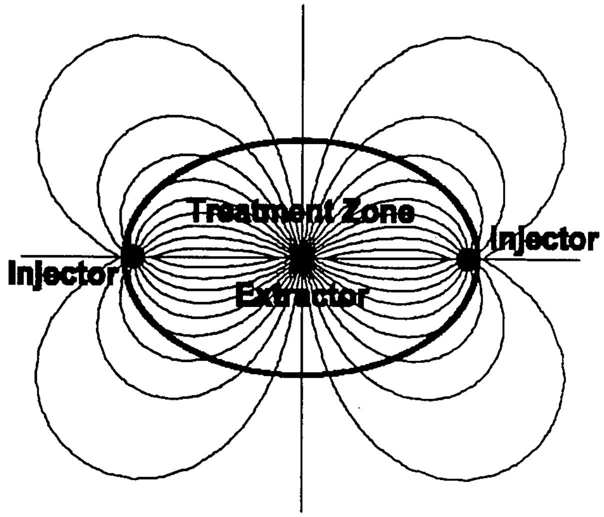
(18) The flow geometry shown in Figure 5-17 applies where the total injection rate equals the total extraction rate. As a result, the flow rate into each injector is one-half of the flow rate from the central extractor. As shown in Figure 5-17, about 60 percent of the flow from injection to extraction 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.

(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 5-17. 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:

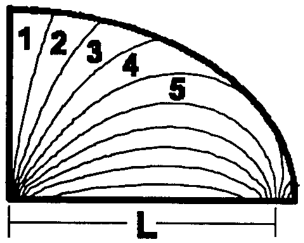
$$t = \frac{V_{\#5}}{\frac{1}{40}Q_v^*} = \frac{0.0956L^2bn_a}{\frac{1}{40}Q_v^*} = \frac{3.82L^2bn_a}{Q_v^*} \qquad (5\text{-}10)$$

where

$V_{\#5}$ = volume of streamtube No. 5 [L^3]



Brailey (1995), unpublished data



Dimensionless Streamtube Areas (x 10^2)

Tube	Area	Tube	Area
1	4.89 L^2	6	6.95 L^2
2	5.25 L^2	7	5.49 L^2
3	6.71 L^2	8	4.84 L^2
4	8.73 L^2	9	4.64 L^2
5	9.56 L^2	10	2.96 L^2

L = well spacing

Figure 5-17. Plan view of streamtubes for a three-well system

To determine the required flow rate, use Equation 5-11 setting the time for one pore volume exchange (t_{ex}) equal to the design criterion:

$$Q = \frac{3.82L^2bn_a}{t_{ex}} \qquad (5\text{-}11)$$

Equation 5-11 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 5-17. 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 5-18. 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 5-11 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 5-18.

(22) As shown in Figure 5-19, four-well systems are best suited for treatment zones that are equant 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 5-19.

(23) The flow geometry shown in Figure 5-19 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

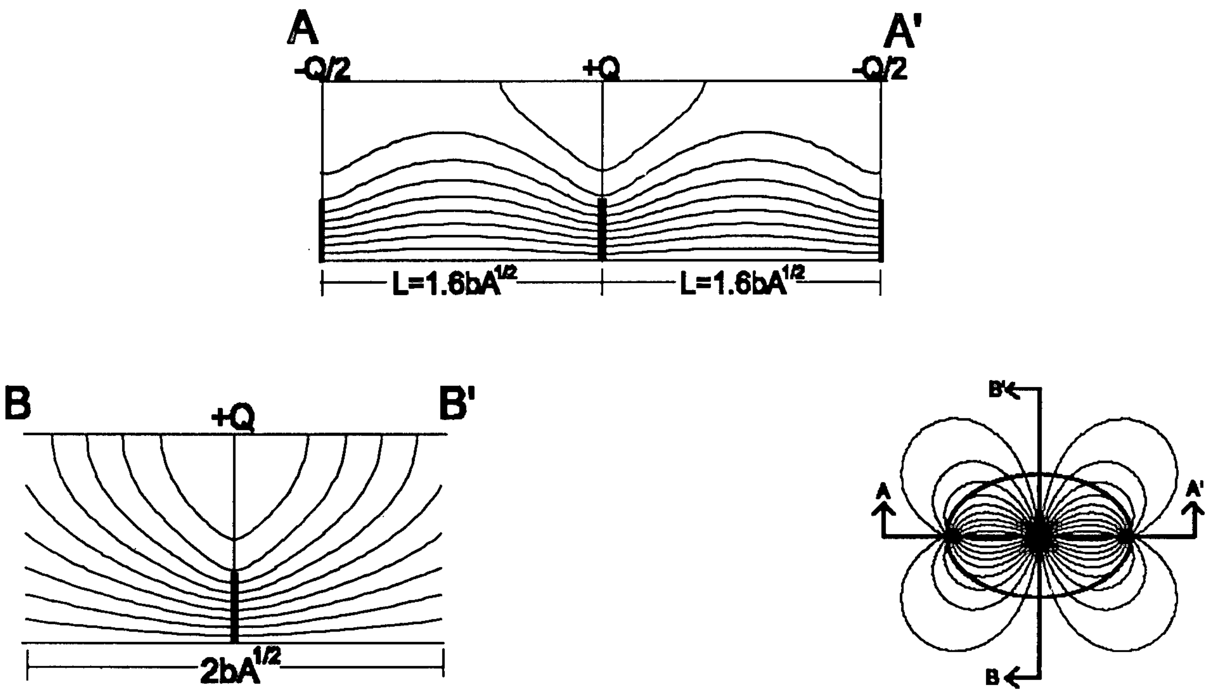
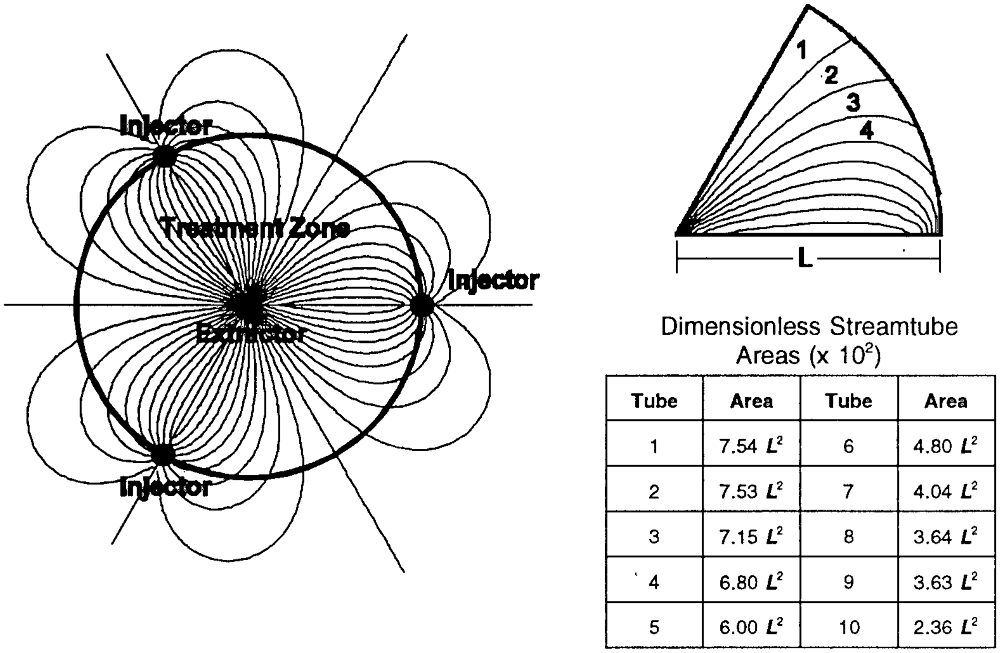


Figure 5-18. Streamtube profiles for a three-well system



Dimensionless Streamtube Areas (x 10^2)

Tube	Area	Tube	Area
1	7.54 L^2	6	4.80 L^2
2	7.53 L^2	7	4.04 L^2
3	7.15 L^2	8	3.64 L^2
4	6.80 L^2	9	3.63 L^2
5	6.00 L^2	10	2.36 L^2

Brailey (1994), unpublished data

L = well spacing

Figure 5-19. Plan view of streamtubes for a four-well system 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 5-19. 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:

$$t = \frac{V_{\#1}}{\frac{1}{60}Q_v^*} = \frac{0.0754L^2bn_a}{\frac{1}{60}Q_v^*} = \frac{4.52L^2bn_a}{Q_v^*} \qquad (5\text{-}12)$$

where

$V_{\#1}$ = volume of streamtube No. 1 [L^3]

To determine the required flow rate, use Equation 5-13 setting the time for one pore volume exchange (t_{ex}) equal to the design criterion:

$$Q = \frac{4.52L^2bn_a}{t_{ex}} \qquad (5\text{-}13)$$

Equation 5-13 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 5-19. 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 5-20. 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 5-13 should be increased by about 50 percent to account for

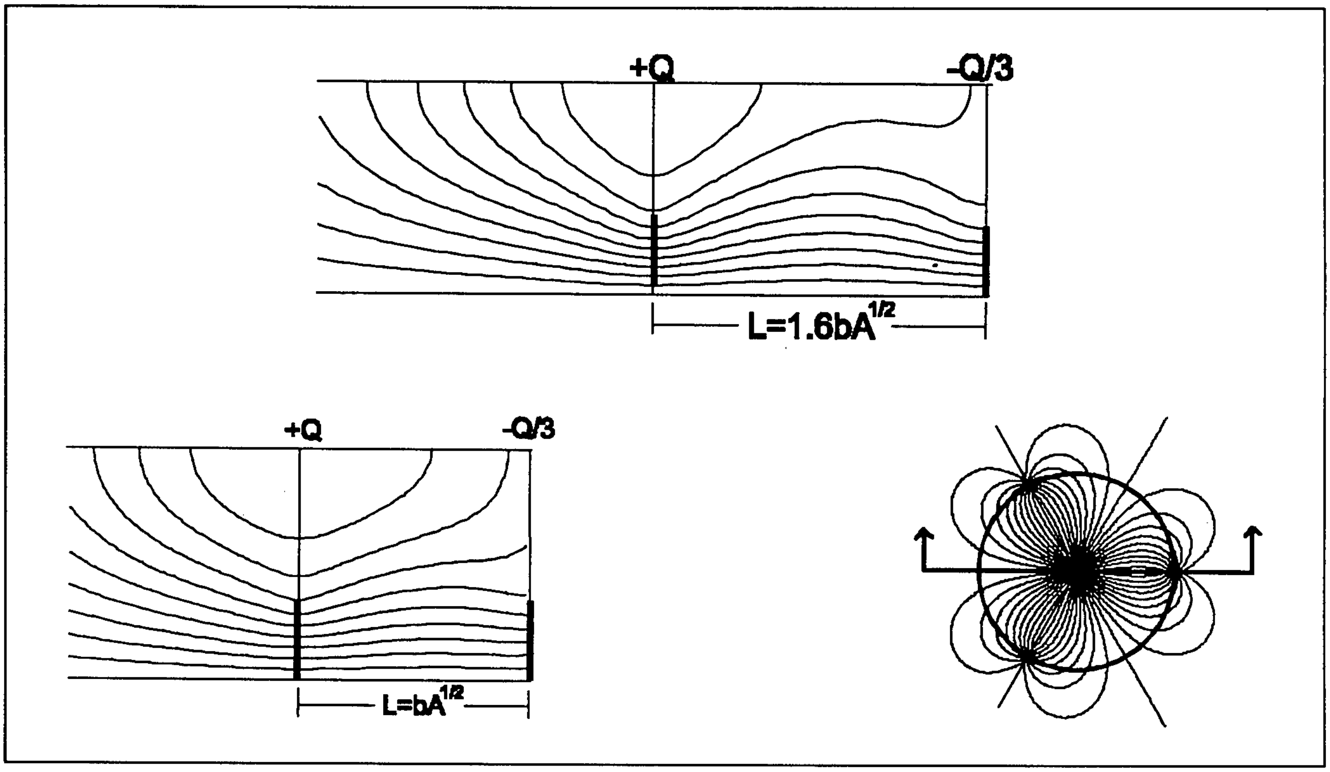


Figure 5-20. Streamtube profiles for a four-well system

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.

(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 5-20.

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 GC with a flame ionization detector (FID) or a photoionization detector (PID).

(4) 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 which 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.

(5) Typically, monitoring probes are constructed with minimal screened intervals so as to characterize parameters at distinct depths. The probes may be installed in clusters with multiple intervals screened to evaluate the variation in parameters with depth. For shallow installations of approximately 7.5 meters or less, hydraulically driven probes may often be used. It is strongly recommended that data be collected in three dimensions to account for heterogeneity and anisotropy of various parameters and conditions. For a single extraction well, this may entail the installation of at least two monitoring point clusters which form a 90-degree angle with the extraction point, or three monitoring point clusters at 120-degree radials from the extraction point. Within each cluster, at least two different depths can 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.

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 lenses of LNAPL. Many SVE systems are operated in conjunction with a groundwater and/or free product recovery system (see paragraph 3-2*d*). 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 CO_2 levels

fall to below 2 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. Well/Trench Construction

a. Vertical extraction wells. This section provides guidance for design and specification of vertical vapor extraction wells (Figure 5-21). 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	D 1785	Specification for Polyvinyl Chloride (PVC) Plastic Pipe, Schedules 40, 80 and 120.
ASTM	D 2241	Specifications for PVC Pressure-Rated Pipe (SDR-Series).
ASTM	D 5092	Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers.
AWWA	A100	Water wells.
NSF	Standard 14	Plastics, Piping Components and Related Materials.
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 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

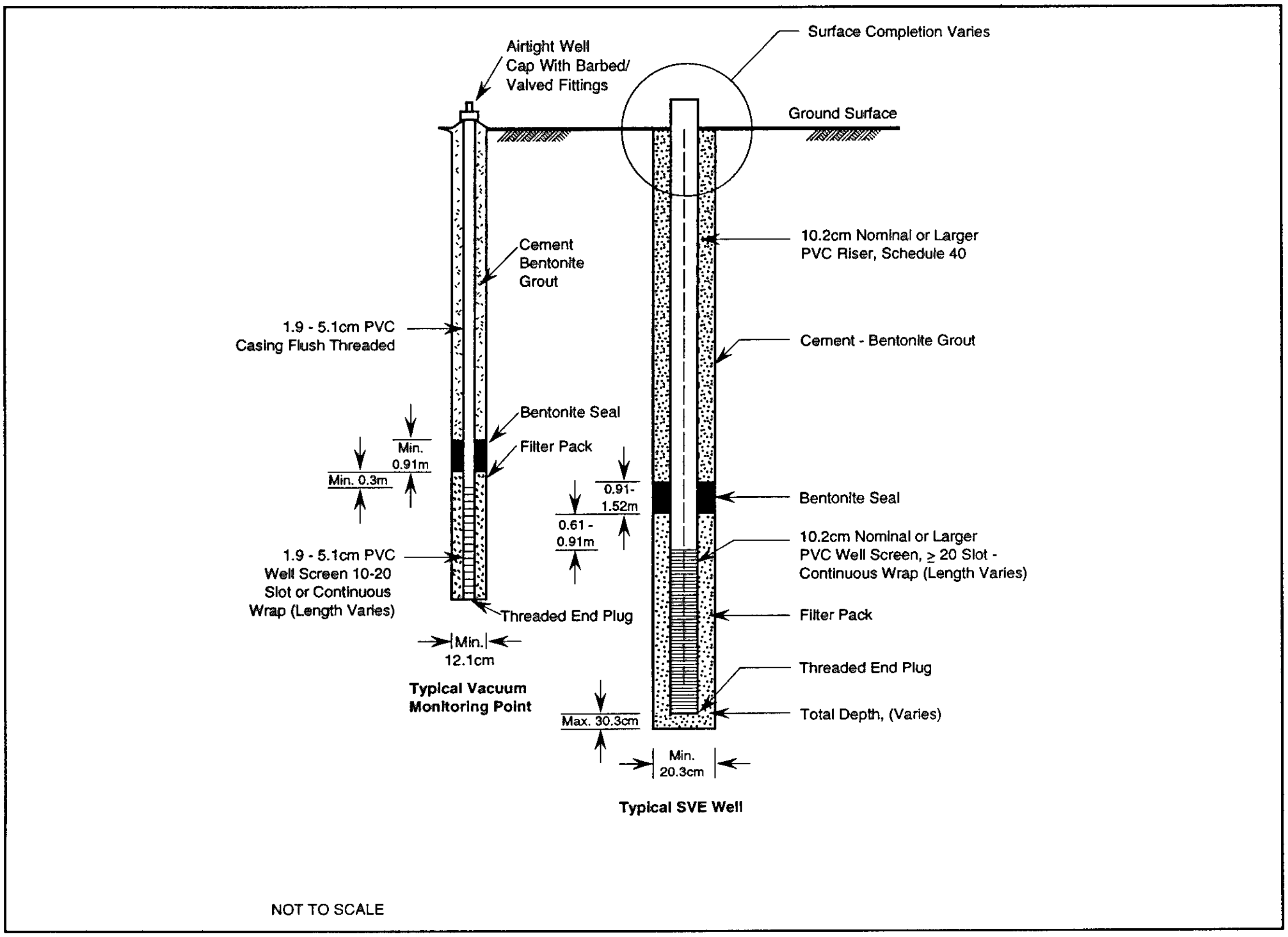


Figure 5-21. Extraction well/monitoring point construction details

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.

(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 slots 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).

(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

Table 5-2
Extraction Well Materials

Components	Operating Size Range		Comments
	Metric	English	
Casing	50 mm 100 mm 150 mm	2 inch 4 inch 6 inch	Sch 40 larger diameters should be used where vacuum losses inside well may be high
Screen	50 mm 100 mm 150 mm	2 inch 4 inch 6 inch	Sch 40 0.5 mm or larger slots
Filter Pack	$C_u \leq 2.5$		Refer to paragraph 5-4*a*(2)(c)
Piping	50 mm 100 mm 150 mm 200 mm	2 inch 4 inch 6 inch 8 inch	Sch 40
Valves (Ball)	50 mm 100 mm 150 mm 200 mm	2 inch 4 inch 6 inch 8 inch	Sch 40
Joints (Elbow)	50 mm 100 mm 150 mm 200 mm	2 inch 4 inch 6 inch 8 inch	Sch 40

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 to further resist cracking), 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. 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.

(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. 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 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 plumbness and alignment, the string should not be allowed to rest on the bottom of the hole. Centralizers should be placed on the casing at regular intervals if the depth of the well exceeds some minimum value such as 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 pipe 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.

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.

(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 multiport monitoring systems are to be used. Multiport monitoring systems are difficult to place and it is often more time-efficient to drill separate holes for the points at different depths in a cluster. Monitoring point depth selection is entirely site dependent, but monitoring of multiple depths within the vadose zone is recommended. It may be appropriate to extend the monitoring point into the water table to monitor water table fluctuations due to seasonal change or in response to the 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. Points placed by direct-push methods may depend on a tight seal with native soil to prevent leaks. Multiport monitoring systems require careful placement of seals between the monitored intervals to prevent "short-circuiting" between the various intervals.

(f) Surface completion. 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.

(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 5-22 illustrates a typical horizontal vent well design.

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

(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 threaded coupling or

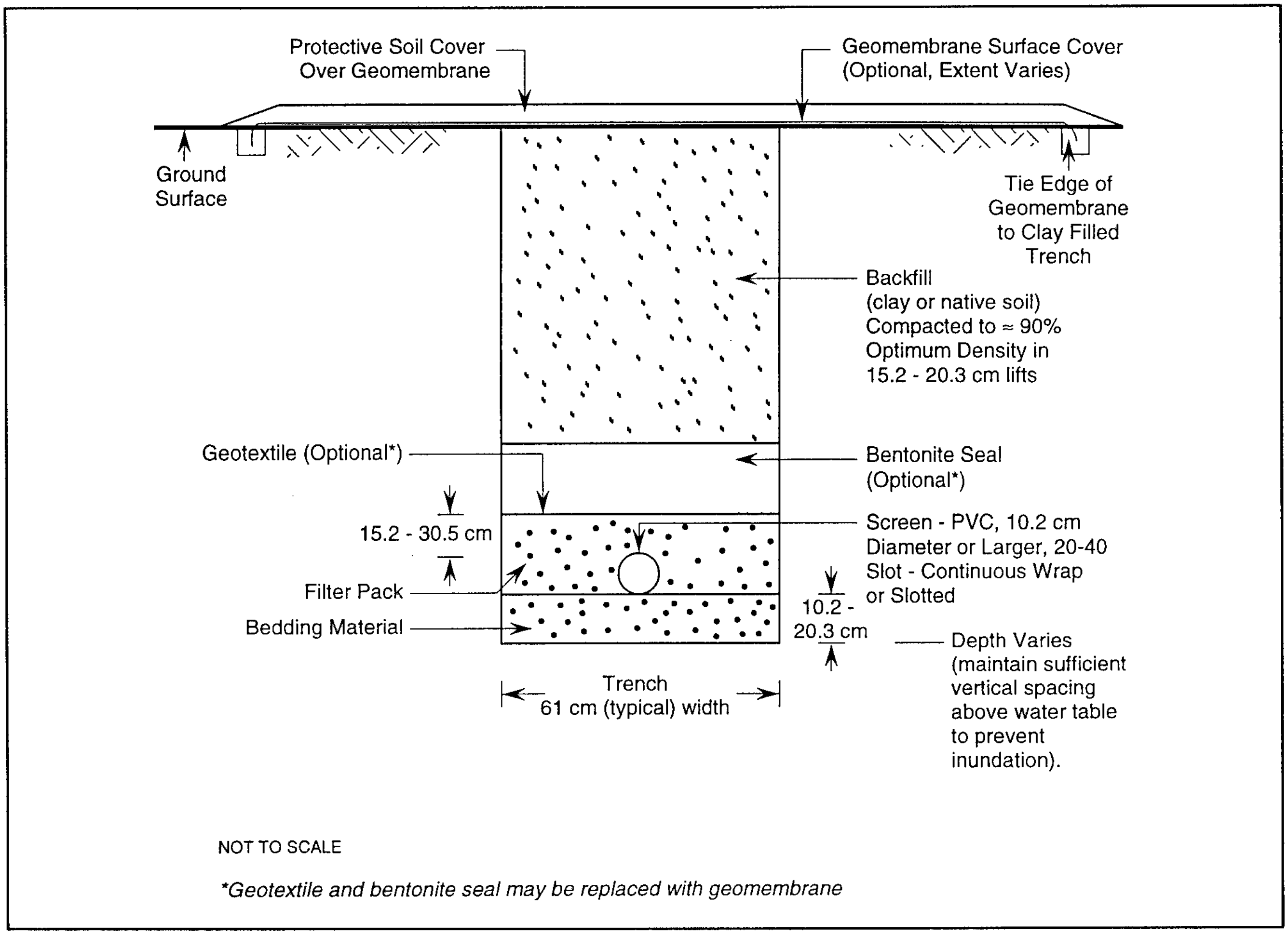


Figure 5-22. Typical horizontal vent well design

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. 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, or a geomembrane, 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 Occupation 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 useof 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.

5-5. 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.

(1) 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, and chemical compatibility.

(2) 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 should even 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.

(3) 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.

(4) 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.

(5) Mechanical stress: Supports for all piping should have a nominal diameter of at least 2 inches. The supports should be designed and spaced in accordance with ANSI/MSS SP-58, -69, -89, and -90.

(6) Pneumatics and hydraulics: Overall system pneumatics were discussed in paragraph 5-2*b*. 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.

(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) The following is a brief description of several valves commonly employed for SVE/BV systems (Figure 5-23):

(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.

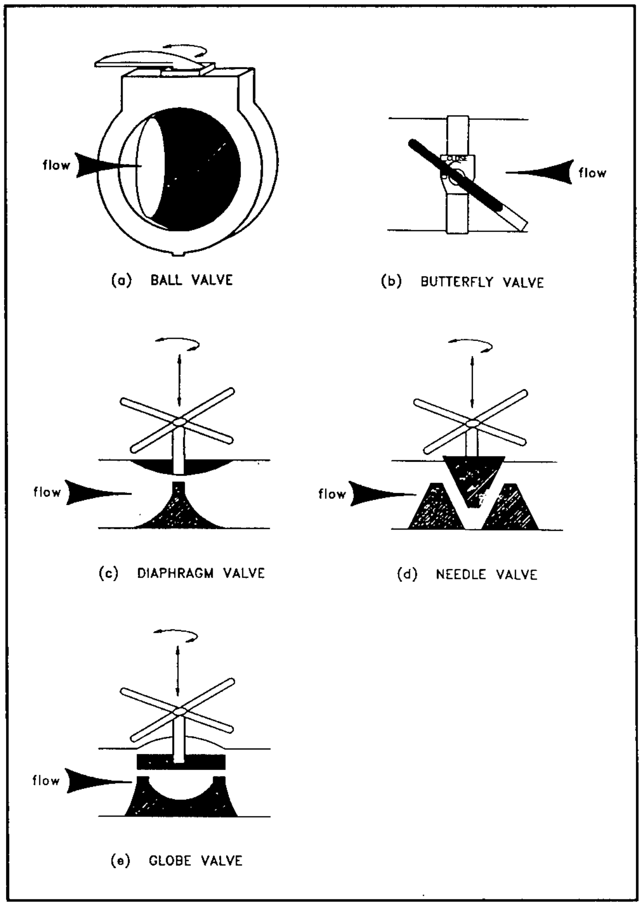
(c) Diaphragm valve - A multiturn valve used to control flow in both clean and dirty services. The diaphragm valve controls flow with a flexible diaphragm attached to a compressor and valve stem.

(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.

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 5-24). 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.



(a) BALL VALVE
(b) BUTTERFLY VALVE
(c) DIAPHRAGM VALVE
(d) NEEDLE VALVE
(e) GLOBE VALVE

Figure 5-23. Valve schematics

(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 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.

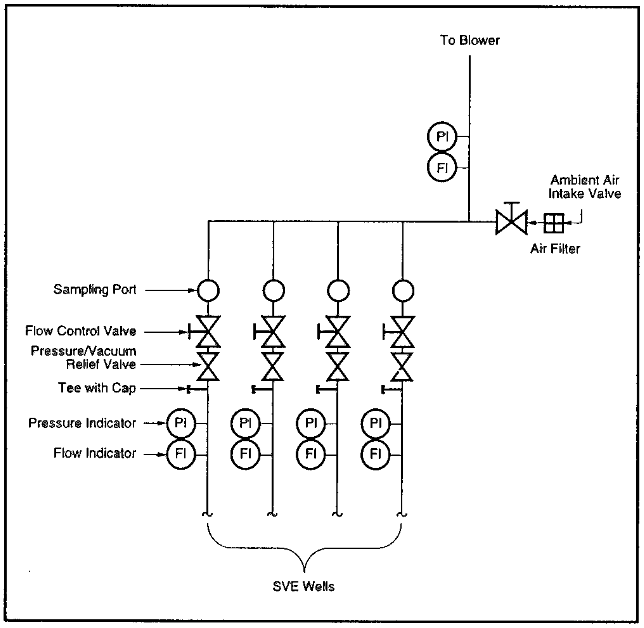


Figure 5-24. Typical manifold system

(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.

5-6. 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 283 °K (65 °F) 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 low temperature, low relative humidity, and low pressure. The low temperature thermodynamically favors 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 (i.e., a rise of 5-15 °C) would be favorable because of humidity reduction, but a large temperature rise (i.e., a rise of 50-100 °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 headloss can occur in the carbon vessel, it may be preferable to locate the carbon downstream of the blower. Also, most carbon vessels will 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 = 8.86×10^{-3} kg/kg air (at 286 °K)

Conc. of water vapor = 3.43×10^{-3} kg/kg air (at 272 °K)

Subtracting, Condensate = 5.43×10^{-3} kg/kg

Use the Ideal Gas Law to estimate the air density.

Density = PM/RT = P/RT = (0.5 atm) × (29 kg/mole) / (0.0821 L-atm/g-mole K) × (303 °K) × (1,000 g/kg)

Density = 5.83×10^{-4} kg/L

where M = 29 kg/kg-mole

The flow rate times the concentration of the condensate in the air (based on the air density in the piping) yields:

(5.43×10^{-3} kg/kg) × (5.83×10^{-4} kg/L) × (236 L/s) × (86,400 s/day) × (1 L/kg) = 64.5 L/day (17 gal/day)

Therefore, 129 liters would be generated in 2 days. Supply one 55-gallon drum to store condensate for the pilot study. This allows for an additional 46 liters (21 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.

$$F = KB_cH_c/D_e^{\,2} \tag{5-14}$$

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)

$$\text{Head loss} = F\,(V^2/2g) \tag{5-15}$$

(4) The condensate separator should be able to withstand the highest vacuum that a blower is capable of exerting. Condensate separators need pumping systems to remove the separated water. These 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.

5-7. 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.

5-8. 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. Issues concerning hearing protection must be addressed in the site safety and health plan. Refer to EM 385-1-1 for OSHA regulations concerning occupational noise exposure. The 8-hour time-weighted-average (TWA) sound level is 85 decibels. The TWA represents an action level for requiring that workers be provided with hearing protection.

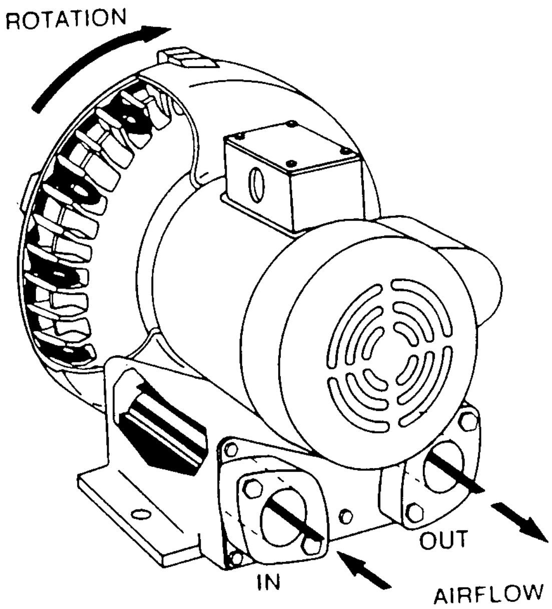
5-9. Blowers and Vacuum Pumps

The pneumatic considerations involved in blower selection have been discussed in paragraph 5-2*b*. The following paragraphs focus primarily on mechanical considerations and the interrelationships among the blower design variables.

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 5-25. 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^3/hr (47 cfm) to 8,000 m^3/hr (4,700 cfm).

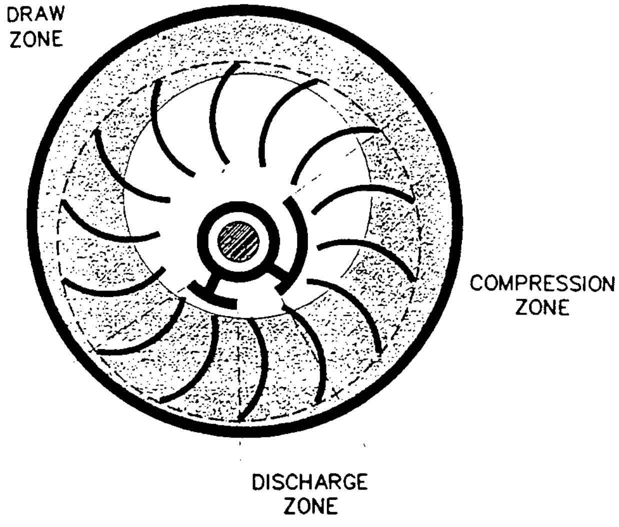
(1) Regenerative blowers. These blowers are typically employed for SVE/BV applications requiring less than 203.2 cm (80 inches) of water vacuum. Regenerative blowers are compact and produce an oil-free airflow. The principle of operation is as follows: A multistage impeller creates pressure through the 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 50.8 to 406 cm or 20 to 160 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

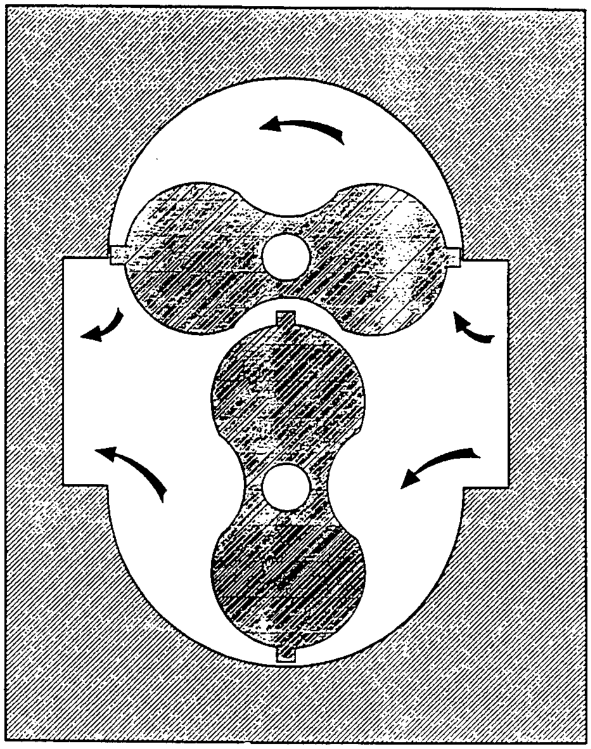


Regenerative Blower Operating Principle

(Reprinted by permission of Rotron Corp.)



Liquid Ring Pump
Operating Principle



Rotary Lobe Blower
Operating Principle

Figure 5-25. Blower schematics

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 5-2*b*). 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:

$$\begin{aligned}\text{power (watts)} = {} & [\text{mass flow rate (kg/s)}] \\ & \times (g = 9.81\ \text{m/s}^2) \\ & \times [\text{change in head (m)}]\ / \\ & \text{efficiency}\end{aligned} \tag{5-16a}$$

or

$$\begin{aligned}\text{power (hp)} = {} & [\text{mass flow rate (lb/s)}] \\ & \times [\text{change in head (ft)}]\ / \\ & ([\text{efficiency} \times 550\ \text{ft} \cdot \text{lb/sec} \cdot \text{hp})\end{aligned} \tag{5-16b}$$

(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 5-2*a*.) 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 blowers 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.

(6) The blower design must specify the explosion-proof classification, i.e., NEMA Class 1, Division I.

c. Tanks and vessels. Pressure vessels and storage tanks must be designed, constructed, tested, certified, and inspected as noted below:

(1) Atmospheric tanks (0-3.5 kPa or 0-0.5 psi) 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, 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. These tanks must be designed and constructed in accordance with the following standards:

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

(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 not 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.
Foundations:	Use allowable bearing pressure on concrete of 8,293 kPa (1,200 psi) for design.

5-10. 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 5-29 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.

(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. 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/SV 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, 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 quickly becomes advantageous to locate the control components in a central location. Centralized control systems are also easier to operate. Centralized data acquisition and control may include the use of computers or 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, 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, avoid hard-wiring the process logic.

(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 also be equipped with auto dialers to alert the operator of a malfunction by telephone or pager. 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 piezometers, LEL meters, organic vapor analyzers, and process GCs.

(1) Monitoring points. Monitor vacuum levels at individual wells or at the treatment system. Pressure transducers and data loggers can be used.

(2) Explosimeter. Must 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 explosimeter probes.

(3) Organic vapor analyzers. Can be used to monitor vapor phase VOC discharges. Units with FID, PID, thermal conductivity, ECD, or infrared detectors are typically employed, 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.

5-11. Electrical Systems Planning

This design guide 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

American National Standards Institute (ANSI)

C80.1	National Electrical Safety Code Specification for Rigid Steel Conduit, Zinc Coated
C80.5	Specifications for Rigid Aluminum Conduit

National Fire Protection Association (NFPA)

30	Flammable and Combustible Liquids Code
70	National Electrical Code
496	Purged and Pressurized Enclosures for Electrical Equipment in Hazardous Locations
497	Class I Hazardous Locations for Electrical Installations in Chemical Plants

Institute of Electrical and Electronics Engineers (IEEE)

141	Recommended Practice for Electrical Power Distribution for Industrial Plants
518	The Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

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. Where these rooms are located within or adjacent to a hazardous area the rooms shall be pressurized in accordance with NFPA 496. All such pressurized rooms shall be provided with means of egress directly to the outside without passing through the hazardous area. Where this is not practicable, a suitable single door systems 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. Basis: NFPA 497.

(b) Enclosed/partially enclosed structures: Adequate ventilation, as defined in NFPA 30, is that which is sufficient to prevent accumulation of significant quantities of vapor-air mixtures in concentrations over one-fourth of the lower flammable limit (LFL). 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 inadequately ventilated location, and is the piping system (containing valves, meters, seals, and screwed or flanged fittings) not likely to leak?

- Is the flammable liquid or vapor being handled in an adequately ventilated location, and can liquid or vapor escape only during abnormal conditions such as failure or rupture of a gasket or packing?

- Is the location adjacent to a Division 1 location, or can vapor be conducted to the location as through trenches, pipes, or ducts?

- If positive mechanical ventilation is used, could failure or abnormal operation of ventilating equipment permit mixtures to build up to flammable concentrations?

(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 which 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 be designed per SAPC Specification E245 and E245A. 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 weather-proof 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.

(b) In hazardous areas, motors shall be temperature rated "T2C" where the "T" rating is as defined per Table 500-2C of the NEC. 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 per information detailed in SAPC Specification I243.

(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.

(b) Design, engineering, and installation criteria shall be per information detailed in SAPC Specification E418.

(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.

Table 5-3
Utilization Voltages

Service	Utilization Voltage	System Nominal Voltage
Motors below 1/2 HP	115 v, 1-Phase, 60 Hz 208 v, 1-Phase, 60 Hz	120 v 240 v
Motors 1/2 HP to 200 HP	460 v, 3-Phase, 60 Hz 230 v, 3-Phase, 60 Hz 200 v, 3-Phase, 60 Hz	480 v 240 v 208 v
Lighting	115/200 v, 3-phase, 60 Hz,4-wire 460 v, 3-phase, 60 Hz, 3-wire 460/265 v, 3-phase, 60 Hz,4-wire	120/208 v 480 v 480/277 v
Noncritical instruments; power and control; telephone equipment	115 v, 1-phase, 60 Hz	120 v
Telecommunication equipment	48 v DC	-
Shutdown systems, alarms, instrumentation	24 v DC with battery backup	-
Critical loads that do not permit Interrupt	120 v, 1-phase, 60 Hz	-
Switchgear control	125 v DC	-
Heat tracing	265/460 v, 3-phase, 60 Hz 115 v, 1-phase, 60 Hz	277/480 v 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 installation shall be in compliance with SAPC Design Guide Z501. 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.

5-12. 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.

(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.

(2) 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 first column is removed from service, the second column is moved up to the first position and the new column (or regenerated column) is installed in the second position. Carbon vessels must be capable of withstanding the temperatures/pressures needed to mobilize the site contaminants.

(3) 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

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 (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 (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 (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 (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 (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 (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 (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 (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

Source: Govind et al. 1994

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.

(4) 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. A relatively small increase in temperature will improve carbon efficiency by reducing the relative humidity, but a large temperature increase would be detrimental to the carbon efficiency. A heat exchanger or chiller could be used to lower the temperature.

(5) There are commercially available adsorption resins which can be used to collect more polar hydrocarbons and solvents which are difficult to collect on GAC. While these materials are traditionally used in wastewater applications, they may be adapted to use on vapor streams. The initial resin expense can be high, but they are usually regenerated to recover solvents or other materials, providing an offsetting return and saving on disposal costs.

(6) Catalytic oxidation is a common means of offgas treatment for SVE systems. The catalyst, often platinum, lowers the activation energy of the oxidation reaction allowing it to proceed at a lower temperature, usually between 550 and 700 °F. The lower combustion temperature results in significant energy savings. Catalyst manufacturers typically claim 95 percent conversion of nonmethane hydrocarbons. A complete catalytic oxidation system may include a burner, a heat exchanger, the catalytic reactor, and a stack.

(7) 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.

(8) 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 will be described in a later section.

(9) Thermal oxidation involves heating the air stream to a temperature high enough for combustion. Thermal oxidizers typically operate between 900 and 1,600 °K. They are generally simpler and more versatile than catalytic systems because there is no need to be concerned with compatibility of the compounds with the catalyst. Although thermal units could be used initially and as long as concentrations remain high, they would be much less efficient after concentrations decline, because supplemental fuel is required at low concentrations. Thus in most SVE applications, thermal oxidation is not economical.

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

(11) 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.

(12) 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.

(13) 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 conditions (especially moisture).

(14) Condensation can sometimes be considered for use if the hydrocarbons are sufficiently high-boiling to be readily condensible and are present in high concentrations. While some product recovery is possible with this approach, materials which are readily condensible 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.

(15) 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).

(16) 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.

(17) 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. 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.

d. Impact on cost. It should be noted that when the full cost of SVE remediation is considered, the operation 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 para. 5-2*a*(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. In multiwell systems, stepped flow reductions, as presented in paragraphs 5-2*a*(10) to (15), are recommended to help minimize extraction and treatment capital and operational costs.

5-13. Summary of Condensate Treatment and Disposal Methods

a. As discussed in paragraph 5-6, condensate is typically collected because the air stream exceeds 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.

5-14. 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 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.

5-15. 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.

c. A synthetic lining 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, ranging from 8 mils to 12 mils in thickness. HDPE linings can be easily rolled out on the site and can be removed when the treatment is complete. Low density polyethylene (LDPE) membranes are preferable over HDPE because they conform to surface irregularities better. Care must be taken to seal the membrane to any installations that penetrate it, such as vent wells, air piezometers, and monitoring wells.

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 mounding 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 shortcircuiting 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.

5-16. Design Considerations for Aboveground Soil Piles

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 3-6 and 3-7 show a typical cross-section and plan view for an aboveground soil pile.

a. Liner system. As indicated in paragraph 3-2*e*, 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 concrete 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.

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 3-2*e*, aboveground soil piles can be constructed to heights ranging from 1 to 3 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.

(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 allow for individual pipe adjustments. 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. Generally, the air flow network manifold parallels the long dimension of the rectangular soil pile. The vents generally parallel the narrow dimension of the soil pile to minimize the effect of pressure head losses described above. In large soil volumes, air flow manifolds on two sides of a soil pile may be considered. Also, construction options may favor multiple soil piles.

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. 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.

5-17. 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 5-26 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 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.

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 5-26. Sample process hazard review

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 then inflow - control failure - faulty level measurement.
MORE PRESSURE:	Surge problems - leakage from inter-connected HP system - gas break-through (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.
MORE VISCOSITY:	Incorrect material specification - incorrect temperature - high solids concentration.
LESS VISCOSITY:	Incorrect material specification - incorrect temperature - solvent flushing.
COMPOSITION CHANGE:	Leaking isolation valves - leaking exchanger tubes - phase change - incorrect feedstock/specification - inadequate quality control - process control upset - reaction intermediates/ byproducts - settling of slurries.
CONTAMINATION:	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.
INSTRUMENTATION:	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/ EROSION:	Cathodic protection arrangements - internal/external corrosion protection engineering specifications - embrittlement - stress corrosion cracking - fluid velocities.
SERVICE 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 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.

5-18. 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 5-27. 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.
- 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 5-28. In this example, soil vapor is extracted from four wells. The well layout resulted from data collection during predesign 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

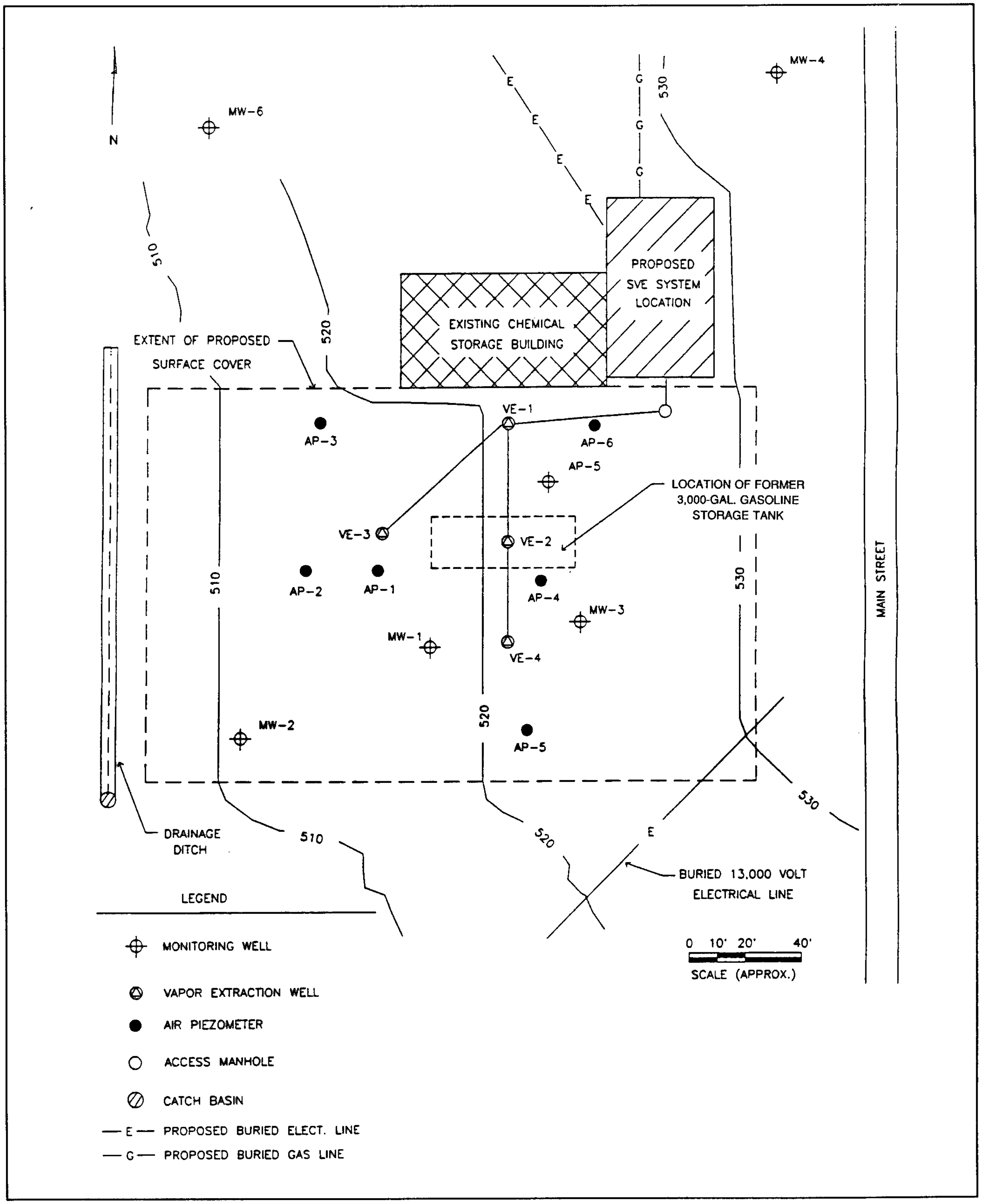


Figure 5-27. Typical SVE site plan

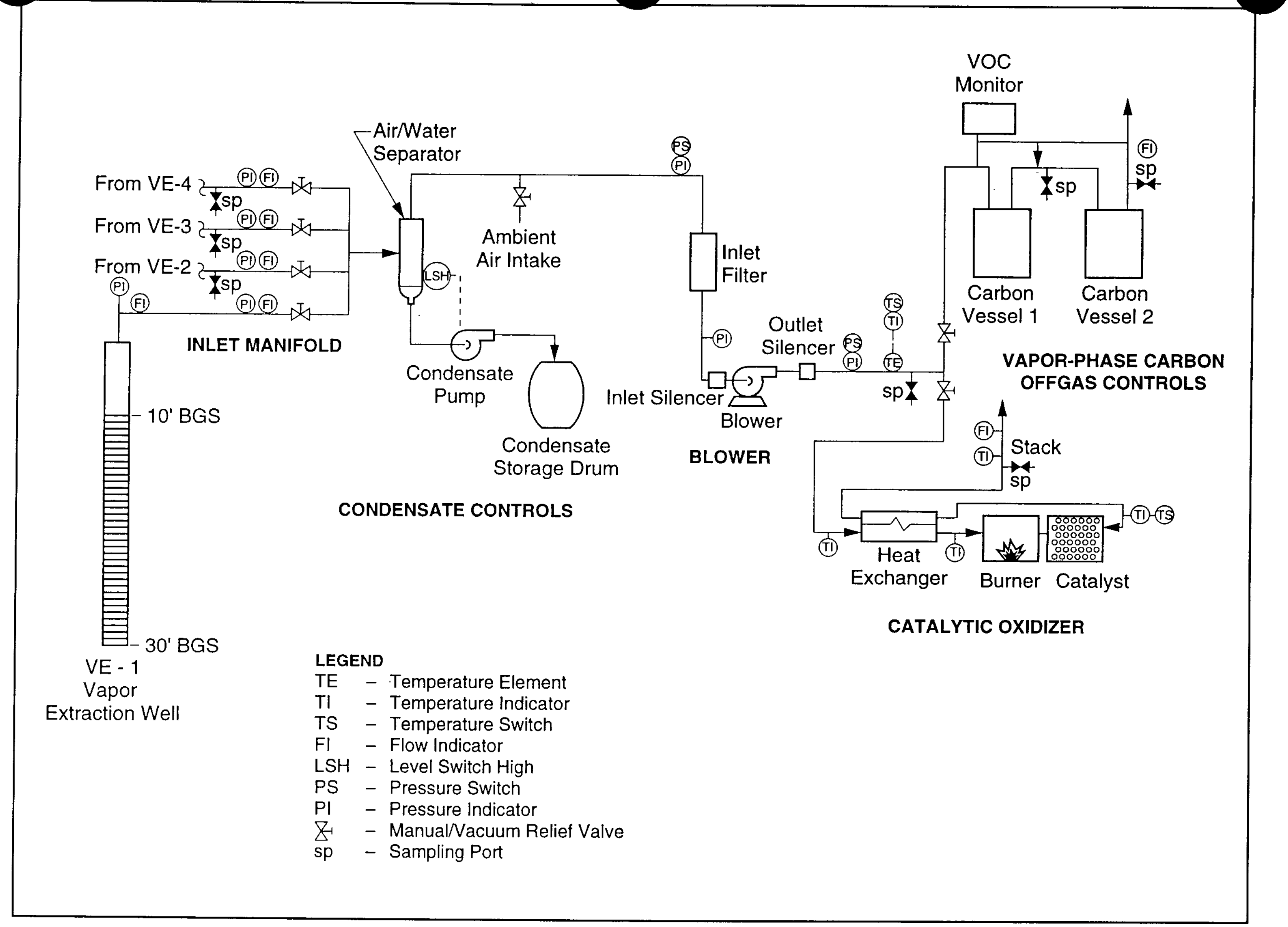


Figure 5-28. Typical SVE preliminary P&I diagram

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.

(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 5-29 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 which 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 log diagram shall be included as part of the electrical control design, if needed for clarification.

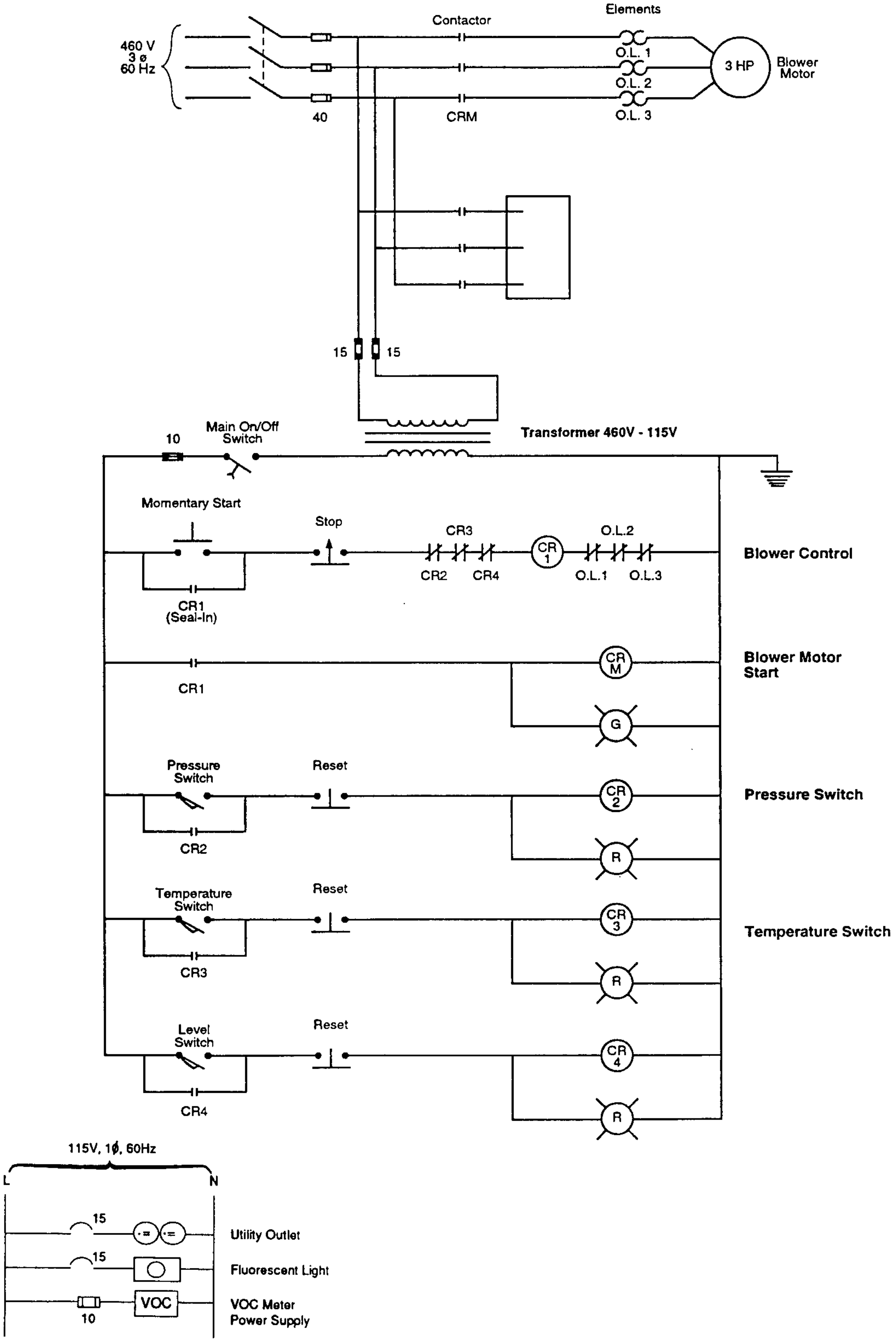


Figure 5-29. Typical SVE electrical analysis

Chapter 6
Design Documents

6-1. Introduction

This chapter discusses the prescribed formats for the development of full-scale design documents for SVE/BV.

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:

Regulation	Title
1110-345-100	Engineering and Design - Design Policy for Military Construction
1110-345-700	Engineering and Design - Design Analyses
1110-345-710	Engineering and Design - Drawings
1110-345-720	Engineering and Design - Construction Specifications
1165-2-132	Hazardous, Toxic, and Radioactive Waste (HTRW)
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.

a. List of specification sections.

(1) Work plans.

01110	Safety, Health, and Emergency Response
01450	Contractor Chemical Data Quality Control
01XXX	Sampling, Analysis, and Disposal of Waste
01XXX	Air/Vapor Monitoring
01XXX	System Startup, Operation, and Maintenance Plans

(2) Site work.

02110	Clearing and Grubbing
02222	Excavation, Trenching and Backfilling for Utilities Systems
02271	Geomembrane Barrier (for Surface Cover)

(3) Well specifications.

02670	Vapor Extraction Wells (Water Well Specification can be modified for SVE/BV wells)
02671	Monitoring Wells/Probes

(4) Treatment specifications.

For example:

11XXX	Vapor Phase Activated Carbon System
11XXX	Vapor Phase Resin Adsorber
11XXX	Thermal Catalytic Oxidation Unit
11XXX	Vapor Condensation System

(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.

15250	Thermal Insulation for Mechanical Systems (if applicable)
11XXX	Blowers

(8) Electrical/control specifications.

16370	Electrical Distribution System, Aerial
16375	Electrical Distribution System, Underground
16415	Electrical Work, Interior

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

(2) Refer also to paragraph 6-3*a* for List of Division 1 through 16 Specifications.

c. Drawings. (Fewer drawings would be required for designs using package systems and performance-based RFPs.)

- Site location.
- Plan and profile.
- Well construction and surface cover details.
- Exterior details.
- Piping layout.
- Piping sections.
- Interior details.
- Power plan.
- Power/control plans.
- Electrical details.
- Lighting, power, and one-line electrical diagrams.

d. Other typically required specifications.

01XXX	Contract Close Out
01XXX	Contractor Quality Control
01XXX	Temporary Construction Facilities
01XXX	Environmental Protection

6-4. Examples of Design Document Formats

Examples of design documents can be found in paragraph 5-18.

Chapter 7
Start-up Requirements

7-1. Introduction

This chapter presents an overall start-up strategy, subsurface system checks, surface equipment checks, analytical measurements, monitoring, reporting, and checklists. The designer and operator are encouraged to review these paragraphs, keeping 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 for each system that takes into account the system's design objectives and complexity.

7-2. Start-Up Strategy

Start-up is comprised of three primary activities:

- Pre-start-up checkout.
- Pre-start-up testing.
- Start-up.

The strategy for start-up is to conduct these activities sequentially, comparing observations and test data against design criteria and performance warranties. This will allow the system to be brought on line in a systematic and safe manner to meet the operational objectives. A checklist for these activities is presented in paragraph 7-8.

a. Pre-start-up checkout. This is an inspection to verify that the components of the system are properly installed. Any foundations should be checked to verify that they are placed properly, sealed properly (if they are coated for containment reasons), and protected from damage while curing. Systems should be checked to verify that all equipment has been installed. Surveying equipment should be inspected for proper alignment, attachment, and level. Protective covers on rotating equipment should be in place. Where rotating equipment requires lubrication, check to ensure that manufacturer's procedures have been followed. 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. The system's P&I diagram is the best document to use to verify that all equipment and piping are installed. As-built drawings should also be inspected and updated as necessary. Where systems transfer liquids or gases, check piping, hoses, ducts, and equipment to be sure that connections are tight. Electrical systems should be checked to verify that wiring has been completed correctly. The electrical One-Line Diagrams and Wiring Diagrams are good documents to use to verify electrical and instrumentation systems. Grounding of equipment and structures should be checked. Protective covers on terminal boxes and panels should be in place. Continuity checks can be performed to verify wiring loops. This is also the time to verify that all the required equipment specified in the Site Safety and Health Plan (SSHP), as well as equipment lockouts, safety valves and/or other pressure relief devices, and site security devices are properly installed. Detailed procedures for operating this equipment should be included either in the site-specific operating manual or the SSHP.

b. Pre-start-up testing. Testing of systems must be performed to verify integrity prior to actual operation. Piping and ductwork transporting liquids or vapors should be pressure or vacuum tested to the design requirement set in the system specifications. Electrical wiring should be tested to verify that there is no wiring damage or deterioration that could cause damage to personnel or equipment. 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. Lighting should be tested and put in service to support work in all areas of the plant. Where cold or hot weather influences progress and operations, the HVAC systems should be tested and put in service. Depending on the complexity of the control systems, testing of control systems can 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. In some cases motors can be "bump" started with hand switches to test rotation of rotating equipment. In other cases, motors will be started from the control system to check the control system as well as the equipment rotation. Care should be taken at this point to be sure that equipment is only "bumped" and not run to avoid damage to the equipment (especially pumps). Instrumentation will be calibrated before systems are put into service and pressure and temperature gauges tested against standardized (calibrated) gauges. 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. Where online gas and liquid sampling instruments are being used, calibrate the instruments after all other system components have been tested. 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 operating tests (start-up).

c. Start-up. Start-up is different for different system configurations. In all cases start-up should proceed slowly with a well-planned sequence of events. This is extremely 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 be put in service without influence on 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 will be energized before process equipment is started. Again, system configurations 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. On systems with vacuum pumps or blowers, set the pressure controls for minimum vacuum and then slowly increase the vacuum once the system stabilizes. Increase the vacuum on the systems incrementally so that periodic inspection of the entire system can be made to ensure proper operation. With systems using thermal oxidation, start with auxiliary fuels to heat the systems before extraction gas is introduced into the unit. If reinjection systems are used, begin with low pressure and increase the pressure step-wise as the vacuum system flow rate is increased. Observation, sampling, and other performance testing 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 points, the entire system should be checked. Check the flow, pressure, and temperature at each extraction well. Check the operation flows, pressures, and temperatures at all test points in the system. 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 a system is started, check for condensate extraction, condensation, and accumulation. Check to see that the condensate removal systems are operating correctly.

7-3. Subsurface System Checks

Of particular concern during start-up are a well's operating conditions, that may be very different than those assumed during design. Often a well 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 this well produce the expected flow for the applied vacuum? Are contaminants removed at the expected concentration? Do remote pressures respond as expected? Start-up provides an excellent opportunity to check design assumptions.

a. Vacuum gauges installed at various locations on the wells and 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. 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 compared with the results of the air permeability test to determine whether any flow rate or vacuum adjustments need to be made.

b. One of the foremost considerations stemming from vacuum/pressure data during start-up is the spatial distribution of pressure around each extraction point. Is the pressure distribution uniform, or are there locations or strata exhibiting much less influence than others? 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. A finding, however, of little or no 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 jet grouting 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.

7-4. Surface Equipment Checks

Numerous components are incorporated into the surface system. Each component must be subjected to the check-out, testing, and start-up activities described in paragraph 7-2 and compared with design criteria.

a. This manual is not intended to describe every potential component and its associated criteria. However, several major components will be common to almost all SVE/BV systems, including:

- Blowers/vacuum pumps.
- Liquid pumps.
- Analytical instruments.
- Control instruments.
- Air/water separators.
- Tanks/vessels.
- Offgas treatment packages.

b. Following the check-out (where each component is compared with system drawings) and testing (where each component is compared with design specifications), the individual components should be checked periodically during the actual start-up using operation monitors such as:

- Pressure/vacuum gauges for blowers/vacuum pumps.
- Pressure gauges and flow meters for pumps.
- Amperage meters for blowers/vacuum pumps and liquids pumps.
- Pressure gauges and differential pressure monitors for offgas treatment packages.
- Temperature gauges for blowers/vacuum pumps and offgas treatment systems.
- Level meters for tanks, vessels, and sumps.

c. A data logging procedure must be established for operating components. Checks should be made very frequently when operation begins and less frequently as the system equilibrates.

d. It is imperative that "in-spec" and "out-of-spec" 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.

e. 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.

f. Once steady-state operation is achieved, operational efficiency data should be collected. These data include:

- Groundwater levels.
- Gas flow rates.
- Applied vacuum at wellhead and in sand/gravel pack around well screen (to determine well efficiencies).
- VOC extraction rates by well and depth (if possible).
- Condensate generation rates.
- Efficiency of offgas treatment.

g. Collection and interpretation of these data are described in Chapter 8.

h. Once the initial data set is evaluated, system adjustments should be made and another round of data collected. This iterative process should be continued until the system reaches a steady-state condition wherein all design criteria are satisfied. At that point, start-up is complete.

7-5. Analytical Requirements

Before start-up of the SVE/BV system, the analytical requirements must be developed. To a great extent, the site characterization data will guide the analytical requirements of the SVE/BV start-up and operations and maintenance phases. It is likely that the SAP that guided site characterization can be modified to guide the start-up of the SVE system itself.

a. Provisions must be in the SAP to ensure that consistent and comparable analyses are employed over the duration of the SVE/BV operation. The periodic analysis of standard reference materials with batches of samples is one good way to ensure comparability.

b. Frequently, sites contaminated with gasoline and diesel range hydrocarbons will be remediated with SVE/BV. In these sites especially, the start-up monitoring must make provisions for health and safety monitoring. Combustible atmospheres must not be allowed to develop or must be carefully controlled if they do exist. Explosivity meters and vapor analyzers, tuned if possible to the appropriate hydrocarbon product or component, must be employed. 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.

c. During site characterization the major components of the contamination will have been identified and methods employed for their quantitation. It is usually sufficient to monitor a subset of these contaminants during start-up, because the remediation of a set of target compounds will be specified in the cleanup plan. The parameters to monitor can be selected based on: prevalence; concentration; volatility; ease of measurement; mobility; representativeness relative to the whole suite of contaminants of concern; and perhaps toxicity. Volatile compounds that are prevalent components of the contaminants and are relatively easy to measure are often good candidates to monitor.

d. In addition to monitoring contaminants, biological indicators should be monitored if BV is an important component of the remediation. Carbon dioxide and oxygen may be measured in subsurface probes and in effluent gas using meters.

7-6. Start-Up Monitoring

a. Field measurements. Field measurements are conducted on a routine basis in order to monitor the efficiency of the SVE/BV system. Field measurements consist of monitoring the blower temperature (i.e., temperature of the air at each point of flow measurement), airflow rate from the blower discharge, vacuum and pressure readings at wellheads and monitoring points, in situ VOC vapor concentrations, and VOC emission concentrations exiting the blower exhauster.

(1) Without annular stabilizing fins, the turbulent nature of airflow in pipes typically causes variations of 15 percent or more in airflow velocity. Pitot tubes or hot wire anemometers can be used to measure flow within this general range of accuracy. Likewise, the sensitivity required for vacuum (or pressure) measurements 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.

(2) Depending on precision, accuracy, and quantitation requirements, vapor concentration measurements can be performed with field instruments or laboratory analyses. Field instruments include flame ionization detectors (FIDs), photoionization detectors (PIDs), explosimeters, and colorimetric detector tubes. Laboratory analyses are usually performed using GCs.

(3) Sampling methods and holding times are an important consideration for laboratory analyses. Samples can be collected in specially manufactured sampling bags, evacuated canisters, or on carbon adsorption media. 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.

b. Measurement of VOC removal rates. Removal rates can be calculated for total VOCs or individual constituents, depending on the type of measurement data obtained. Total VOC measurements can be acquired with

FIDs or PIDs. Although PIDs respond better to halogenated and aromatic hydrocarbons, FIDs provide a good general response to all hydrocarbons. Whereas these field instruments can quantify only total VOCs, GCs can quantify individual constituents as well as total VOCs. Standards used for calibration of field instruments or GCs should be representative of the approximate composition of the target VOCs.

(1) Samples for measurement of VOC removal rates are collected from the sample port located ahead of the offgas treatment system. The total VOCs are commonly measured using a PID, either by insertion of the PID probe tip into a sampling port or by collecting a Tedlar bag of exhaust vapor for analysis. In order to identify specific compounds exiting the SVE/BV system, a GC with a FID is commonly used. The air sample is collected either with a syringe (for field GC) or in a Tedlar bag for laboratory analysis. If carbon treatment is used on the vacuum side of the blower, vapor samples will have to be collected before the carbon canister using a metering pump to fill Tedlar bags, or using airtight glass syringes. In order to determine the VOC removal rates, certain calculations must be performed. Table B-1 presents the molecular weights of some most common VOC compounds, and Table 7-1 illustrates how the calculations are performed. Conversion of the temperature and pressure of a gas to standard temperature and pressure (STP) is described in basic texts (Mortimer 1986).

(2) VOC removal rate calculations are typically presented as contaminant removal versus time (see Figure 7-1). Cumulative concentrations can also be plotted (refer to Figure 7-2).

c. Groundwater level measurements. Groundwater level measurements are required to evaluate the effects of water table upwelling on system performance. Water table upwelling can submerge contaminated soils near the water table, rendering them inaccessible to vapor flow. Water table upwelling also reduces the thickness of unsaturated soil near individual vents, limiting the available airflow. The effects of water table upwelling can be reduced by lowering the applied vacuum, installing additional extraction vents, installing air inlet vents, and/or by dewatering.

(1) 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 3-2*d*). Direct measurement of water table upwelling requires the wellhead to be sealed (preventing loss of the applied vacuum) at the time of measurement.

(2) 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 4-5*e*(18).

7-7. Start-Up Report

Despite the available analytical and numerical models, actual hydrocarbon recovery rates are difficult to predict prior to system operation. Since recovery rates are directly related to the required treatment time, the achievable cleanup levels, and offgas treatment requirements, actual recovery rates are a controlling factor for ultimate cleanup costs. Therefore, an important component of the start-up report is the estimation of future recovery rates.

a. Sustainable hydrocarbon recovery rates can be estimated by plotting discharge concentrations versus time. As shown in Figure 7-3 discharge concentrations typically show an initial spike, followed by a rapid decline to a sustainable contaminant concentration ranging from 1 to 10 percent of the initial concentration. In Figure 7-3, 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. The flow rate does not change appreciably in these examples. Depending on the airflow rate, the treatment volume, and in situ concentrations, periods ranging from one day to one month may be required to determine the sustainable discharge concentrations. Once sustainable concentrations have been achieved, the actual contaminant recovery rates can be calculated as described in paragraph 7-6*b*(1). 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. This calculation may be compared with the column test results described in paragraph 4-7*a*.

Table 7-1
Total Hydrocarbon Air Emission Calculations

$ER = [(Q \times C \times MW \times 2.68 \times 10^{-3})\ (kg/1000g)]$

where

ER = emission rate (kg/hr)
Q = blower pumping rate (m^3/min)
C = soil gas concentration (ppm-v)
MW = molecular weight of contaminant (g/g mole)

The constant (2.68×10^{-3}) has units of [(g-mole min)/m^3 ppm-v-hr)] and was derived in the following manner:

$[(1/10^6 \text{ ppm-v}) \times (60 \text{ min}/1 \text{ hr}) \times (1\text{g-mole}/0.0224\ m^3)] = 2.68 \times 10^{-3}$

CALCULATIONS

Q = 7.08 m^3/min
C = 302 ppm-v (total hydrocarbons)
MW = 177 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 Kg/hr
ER = 24.2 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

b. 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, hence, VOC removal rates. The system balance should be checked periodically throughout the remediation program (bimonthly to start) to ensure that the optimum balance is re-determined, as the concentrations will change over time.

c. The start-up report should contain the following information:

- Data tables of test observations (flow readings, vacuums, concentrations, and levels).
- Influences (weather conditions, mechanical or electrical problems, times and durations).
- Predicted versus actual system performance (Figure 4-17 versus 7-3).
- Discharge concentration results (Figure 7-3).
- Any differences between planned performance and actual results.

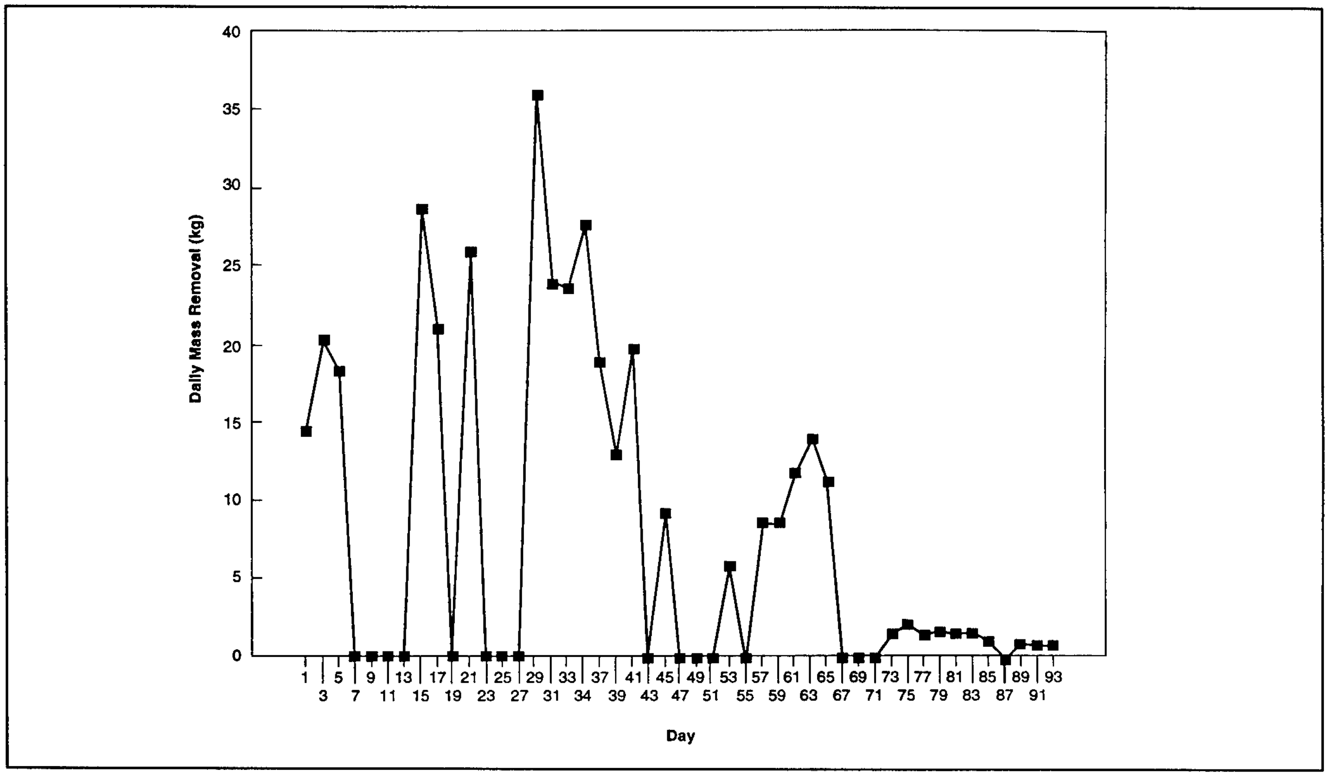


Figure 7-1. Daily contaminant removal

- Problem/incident reports.

- Implications of actual start-up performance on remediation schedule.

d. The start-up report should also address the accuracy of design parameters. The actual radii of influence, pressure-flow relations, liquid recovery rates, explosion hazard control, and offgas emissions should be presented. Potential problems and corrective actions can then be addressed.

7-8. Start-Up Checklists

Tables 7-2 and 7-3 present suggested checklists for start-up activities, beginning with commissioning (pre-start-up checkout and testing) and concluding with the Functional Performance Tests Checklist (the actual equipment start-up). Individual offices should develop similar forms which meet their specific needs. The sequence terminates when the system is on-line and equipment performance is documented to comply with specifications. The checklists are adapted from USACE Guide Specification 15995, "Commissioning of HVAC Systems."

a. 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 less pressure drop through the soil). 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) For most SVE/BV sites, the highest concentrations of VOCs will be present at the beginning of remediation and will fall off substantially within the first two to six months. Often the most challenging design problem is the treatment of the final "hot" areas within the original contaminant plume. The air treatment system must be capable of meeting permit requirements

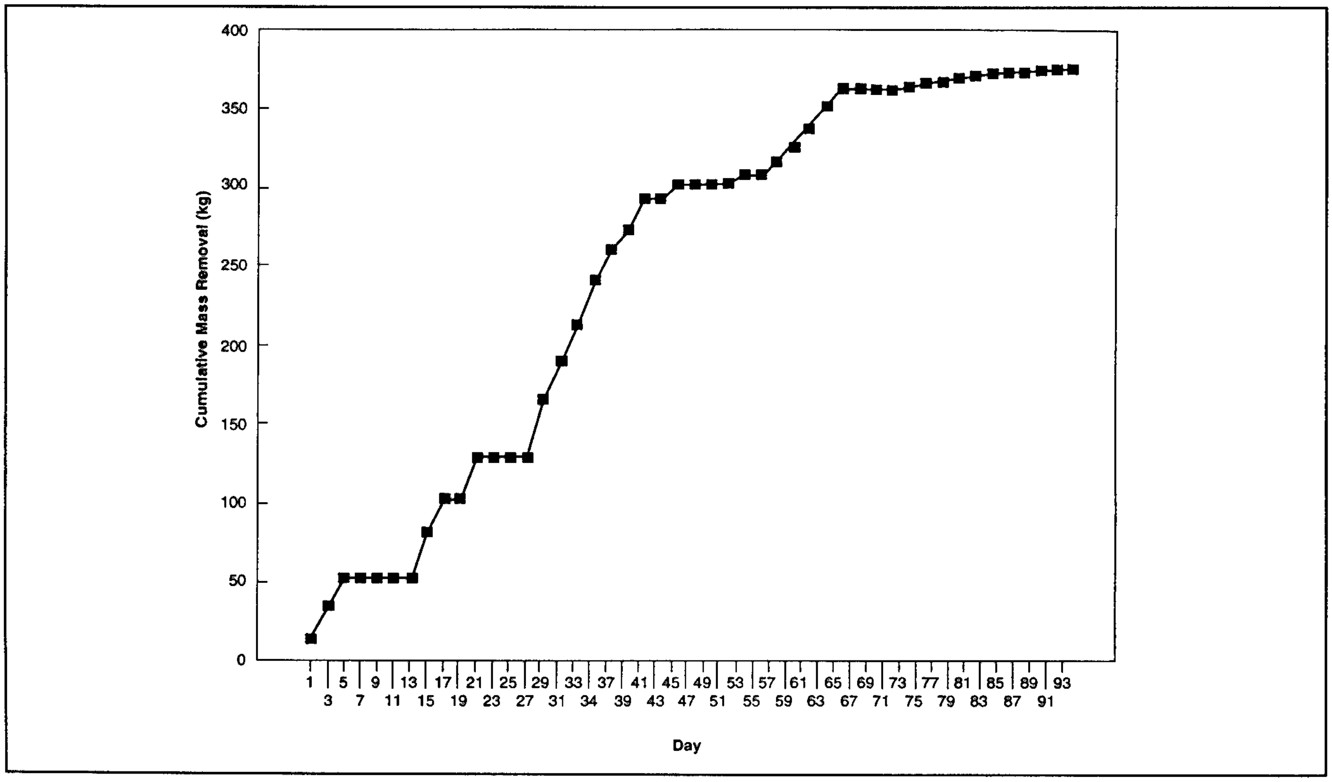


Figure 7-2. Cumulative contaminant removal

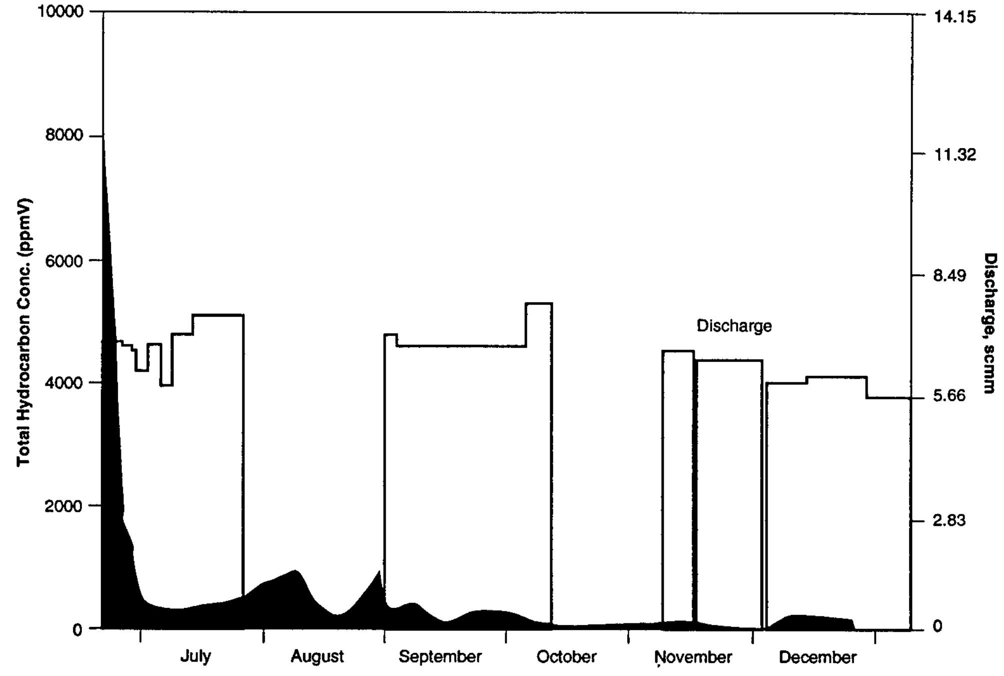
throughout the operating concentration range, and its efficiency at low concentrations may be checked during the pre-start-up testing.

(3) 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.

b. 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 will be initialed by the appropriate team member at completion and acceptance of a particular item.

c. The commissioning checks and functional performance tests should be performed in a manner to duplicate the vendor's recommended procedures. If no vendor procedures are provided, methods must be developed to meet the information needs of the checklist. Any deficiencies must be corrected and retested to meet contractual requirements.

d. Functional performance tests begin after the pre-commissioning checks have been successfully completed. The performance testing begins with equipment or components, proceeds through subsystems, and ends with the complete remediation system passing its performance specifications and contractual requirements testing. Any deficiencies must be corrected and performance checks successfully completed before the system can be accepted.



Source: Adapted from Brailey and Rog 1989

Figure 7-3. Total hydrocarbon concentration

Table 7-2
Suggested Precommissioning Checklist

Checklist Item	Responsible	Initials	Date
Subsurface			
Wells/trenches installed per specification			
Wells purged/cleaned			
Monitoring points installed			
Temperature/pressure gauges installed on wellheads and monitoring points			
Underground piping to pumps installed/tested			
Piping Installation			
Piping complete (including from wells/trenches)			
Piping flushed/cleaned			
Strainers/filters installed/cleaned			
Valves installed and operation verified			
Insulation/heat tape installed			
Thermometers and gauges installed on piping			
Pressure test complete			
Pumps			
Foundations complete			
Pumps grouted in place			
Vibration dampers installed			
Coupling alignment/level to specifications			
Pipe connections installed/tested			
Pumps and seals intact (no leaks)			
Electrical			
Grounding installed/checked			
Lighting/HVAC functional			
Lockouts/covers/panels in place			
Pump rotation verified			
Disconnects in sight of unit being controlled			
Controls/alarms and interlocks functional			
Power connected to monitoring instruments			
Subsystems			
Instruments calibrated			
Air treatment system installed/functional			
Auxiliary fuel (if needed) operational			
Liquid ring fluid system functional (if needed)			

Table 7-3
Suggested Functional Performance Checklist

Checklist Item	Responsible	Initials	Date
Subsurface			
No piping/well pneumatic leaks			
Water level rise within specification tolerances			
Monitoring point compositions within expected ranges (if measured)			
Monitoring point pressures and temperatures within expected ranges			
Pumps			
Start/stop from all control mechanisms			
Operating points match pump curve specification for flow rate vs. vacuum through start-up			
Current draw and voltage balance match specifications for all phases			
Support systems (water for liquid ring systems, fuel for catalytic combustion systems) operate within specification			
No excessive vibration/noise/temperature rise			
Systems			
Air treatment system performance meets specifications			
Control system operates within set parameters			
Monitoring systems/instruments hold calibration			
Mass removal rate follows expected data trends			

Chapter 8
Operations and Maintenance

8-1. Introduction

This chapter presents overall operation and maintenance (O&M) procedures for an SVE/BV system.

8-2. O&M Strategy

This section presents an overview of a typical O&M strategy, including operational guidelines, monitoring parameters, and system modification considerations. Table 8-1 is a troubleshooting guide for major operational decisions for 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 O&M plan should include contingencies for possible operational problems.

a. The system O&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. One important aspect of the overall strategy is to collect data frequently in the early, transient stages of operation, and reduce the sampling and monitoring frequencies after the system achieves 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 ensure the continuity of trends. It is important that complete and thorough data sheets are maintained and reviewed in order to track these trends.

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, injection of hot gases, and pneumatic fracturing. Consequently, it will be important to monitor information that would influence the transition to or modification 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. The radius of influence will be larger during the periods that fewer wells are operating at higher flow rates. 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 would 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 (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

Table 8-1
SVE/BV System Operation Strategy and Troubleshooting Guide

Problems	Considerations	Potential Solutions
The radius of influence of vacuum levels is insufficient or not as predicted	The soil may be less permeable in some locations or there may be preferential flow	Further subsurface investigation Readjust flows Additional wells Check wells for clogging Check for short-circuiting
Vacuum levels are spatially inconsistent	There may be preferential flow or heterogeneities	Further subsurface investigation Additional wells 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 flows to some wells Take some wells offline Check for ongoing sources of contamination
The VOC concentrations remain consistently high despite high mass removal rates	Undiscovered groundwater contamination or free-phase product	Further investigation Product recovery Groundwater remediation Air sparging
Low concentrations of VOCs are extracted during operation, but high concentrations reappear when system is shut off	Diffusion limitations, flow short-circuiting due to preferential flow, soils too moist, airflow rates higher than necessary	Dual recovery Pulse venting Hot gas injection 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	BV Pulse venting Soil heating
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 Activated carbon Biofilters Use other technologies to speed up removal 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 Dual recovery Shut off system following major rain events
Unexpectedly high vapor concentrations at or near explosive levels	Free-phase product; Accumulation of methane or other VOCs	Dilute intake air Alter system to be explosion-proof Check for unknown sources of contamination

(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 7-3).

(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

Table 8-2
Suggested SVE/BV System Monitoring Checklist

Physical Characteristics

Atmospheric pressure
Pressure at extraction well(s)
Pressure at monitoring wells
Blower inlet vacuum
Blower outlet pressure
Ambient temperature
Vapor temperature at wellhead
Temperature at blower discharge
Temperature at treatment effluent
Wellhead volumetric airflow rate (acmm)
Blower inlet flow rate (acmm)
Treatment effluent flow rate (acmm)
Bleed rate
Blower amperage
Volume of condensate
Soil moisture content
Relative humidity
Groundwater elevation(s) near extraction well(s)
Degree of upwelling
Volume of groundwater removed (if any)
Volume of free product removed (if any)

Chemical Characteristics

Contaminant concentrations at extraction well(s)
Contaminant concentrations at blower inlet and/or outlet (as appropriate)
Contaminant concentrations at treatment midpoint
Contaminant concentrations in treatment effluent
Contaminant concentrations in soil gas at monitoring points
Contaminant concentrations in extracted groundwater
Contaminant concentrations in condensate

Biological Characteristics (see Table 3-1 for analytical methods)

Oxygen concentrations
Carbon dioxide concentrations
Microbial respiration rate (shutdown tests)
Nutrient concentrations (e.g. nitrogen and phosphorus)
pH

oxygen uptake rate diminish. These systems are typically controlled by monitoring the concentrations of oxygen in the vadose zone and assuring that the concentration does not decrease below a predetermined level capable of supporting aerobic biological activity (e.g., 5 percent O_2). Sorensen and Sims (1992) suggest that there are advantages to alternating between anaerobic and aerobic conditions during pulsed venting. Anaerobic conditions would allow for several beneficial reaction pathways such as nitrogen fixation, fermentation, and reductive dechlorination.

g. Aboveground soil pile treatment system operation.

(1) O&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 of appropriate size, or installation of an automated knockout drainage system.

8-3. Monitoring

Monitoring methods are also described in Chapters 3 and 4.

a. Physical parameters.

(1) Pressure measurement. Pressure readings 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 flow rate measurement. Vapor flow rates should 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.

(a) 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. Measurements can be made using a variety of flow meters, including rotameters, orifice plates, hot-wire anemometers, and pitot tubes.

(b) It is important to note that the conversion of flow rates from actual cubic meters per minute (acmm) to standard cubic meters per minute (scmm) is necessary because the density of the extracted gas, which depends on the temperature and pressure, can vary as it passes from one monitoring point to another. This conversion is as follows:

$$\text{scmm} = \text{acmm} * [293\ {}^\circ\text{K}/(273 + {}^\circ\text{C})] * [(\text{cm H}_2\text{O} + 1{,}036)/1{,}036 \text{ cm H}_2\text{O}] \qquad (8\text{-}1)$$

This equation can be used prior to calculating air emissions (Table 7-1).

(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 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, typical piping 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 or with electronic thermocouples that 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. The relative humidity can be monitored to determine the effectiveness of the condensate control system described in paragraph 5-6. Humidity sensors can be installed at the blower or activated carbon inlet and can be used to control a humidity reduction or an air heating system.

(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 paragraphs 4-5*e*(18) and 7-6*c*. 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. The volume of water removed from the vapor stream should be monitored. The amount of water can be determined by placing a sight glass on the tank and computing the volume contained.

(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 3-2*d*), 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 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, and methods for sampling and analysis.

(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 7-6*a*, 7-6*b*, and 3-3*d* for more detail regarding field and laboratory analyses.

(3) System shutdown criteria, which will be discussed in the next section, 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 may be accomplished by either process instrumentation or 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. This mass removal can be compared with an estimate of the initial mass of contaminants in the subsurface. A complete mass balance would also include the mass of contaminants that are biodegraded.

(7) Chemical monitoring of the subsurface will also help gauge the progress of the remediation. VOC samples can be obtained from soil gas probes, air piezometers, or monitoring wells. Monitoring the concentrations of oxygen, carbon dioxide, and sometimes methane helps establish the level of biological activity in the subsurface.

(8) Chemical analysis of accumulated condensate is usually required for disposal purposes.

c. Biological. Monitoring of biological activity can be accomplished by several means. The heterotrophic plate count, formerly known as the standard plate count, is a procedure for estimating the number of live heterotrophic bacteria in water. The method can also be adapted for soil samples. Plates containing a medium with food and nutrients are inoculated with the 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 included in the term "colony-forming units." Several different methods (including pour plate, spread plate, and membrane filter method) and different media are described in APHA/AWWA/WEF (1992). The pour plate method is commonly used for bioremediation monitoring. Inexpensive plate counts are routinely performed by commercial laboratories. While plate counts alone provide only an indirect, and rather imprecise measure of the useful biological activity at a site, especially 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.

(1) Other 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) Respiration rate determinations. Concentrations of oxygen and carbon dioxide are routinely monitored during BV operations using portable meters. Decreased oxygen and increased carbon dioxide concentrations can provide an indication of biological activity. If one assumes a stoichiometric relationship between oxygen consumption or carbon dioxide generation and contaminant biodegradation, contaminant 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. Having fewer abiotic sources and sinks, oxygen is generally recommended over carbon dioxide for determining biodegradation rates (Ong et al. 1991).

(3) Significant deviations from ambient conditions are possible in soil gas. Dry atmospheric air contains approximately 20.9 percent oxygen and 0.03 percent carbon dioxide. Prior to BV at one site, 0 percent oxygen and 26.4 percent carbon dioxide were measured in soil gas (Hinchee, Ong, and Hoeppel 1991b). 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. This information can also be used to optimize BV flow rates. 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 sample collection is typically completed 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.

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 seal must be replaced.

8-5. Vapor Collection System O&M Considerations

a. O&M design considerations. Operations and maintenance 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 O&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 O&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. Instrumentation and control. Providing instrumentation and control systems can reduce the time an operator needs to be on site and, therefore, operations cost. Systems can include automatic control, monitoring, and shutdown sequences, and a telephone dialing and reporting system that will call operators when systems reach critical points or shutdown. These systems of course increase SVE/BV system capital costs.

d. 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 deviate temperatures even higher, 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 explosion 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, internal parts could come loose and cause sparks. These sparks can cause flash fires. Spark arrestors should be included in the piping or ductwork to reduce the possibility of fires.

(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 5-11*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 prepared a guide on hazardous materials (1984) which includes data on flashpoint, specific gravity, water solubility, hazard identification, and boiling point 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) 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 should back up these shutoff systems.

e. 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.

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 Modifications/Optimization

Most system modifications are made because the air movement 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.

a. The well spacing will typically include some overlap of coverage to ensure adequate contaminant removal from the subsurface. Optimization becomes necessary 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; clean areas may be disconnected from the SVE/BV system to concentrate airflow on the more contaminated areas.

b. 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 and subsequent introduction of water into the vacuum system. This can sometimes infuse a carbon canister with water if it is on the vacuum side of the pump. A cyclonic separator may be overloaded very quickly if water is entrained in the air stream.

c. 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.

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.

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

Table 8-3
Routine Maintenance Items

Periodically drain the water that has accumulated within the PVC 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, decrease the vacuum.
Verify that the demister and demister 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, regrease blower assembly per manual.
Approximately every 1500 hours, change oil in blower assembly suitable to ambient conditions for the next quarter.
Periodically check and clean particulate filters.

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 air movement is as expected.

c. Check valves and other valving. A check valve should be installed between the well and the pump to ensure that air is not 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 needs its own valve to control the flow through the system.

d. Air treatment. The operating problems associated with carbon systems are usually minimal as long as the air is filtered and dehumidified. The carbon exhaust needs regular monitoring 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.

e. Control systems. Operating problems with control systems are usually caused by electrical problems in the controller, which requires a service call from the equipment supplier, 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 help this situation.

8-10. O&M Protocol

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 O&M activity properly.

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

 B. Description of Facilities

 C. Project Organization

II. Description of System Components

 A. Well Configuration and Construction Detail

 B. System Piping and Instrumentation

 C. Vapor Collection System

 D. Vapor Pretreatment System

 E. Vapor Treatment System

 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 Inspections

 B. Routine Maintenance Procedures

 C. Consumables and Spare Parts Inventory

VI. Sampling, Analysis, and Reporting Documentation

 A. Remediation Goals

 B. Discharge Limits

 C. Sampling and Analysis Schedule

 D. Reporting

 E. Quality Assurance

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 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.

EXAMPLE SECTION

V. System Maintenance

 A. Weekly Inspections

The treatment system will be inspected on a weekly basis. Any failures, faults, or unusual observations will be investigated fully. Any equipment that is found to be faulty, out of adjustment, or in disrepair will be repaired or serviced. Manufacturer's information for the major pieces of equipment is provided in the Appendix to this O&M manual. In general, after the start-up period, very little ongoing maintenance is required for the equipment used in this SVE/BV system. The required weekly inspection items are listed below:

- Extraction Well Head and Influent Manifold:

  Inspect both the groundwater and vapor extraction wells and piping for evidence of tampering or damage.

- Vacuum Collection System:

  Inspect the blower for signs of improper operation, such as abnormal noise levels, excessive vibration, or overheating. Check particulate filter and clean or replace if necessary. Check air-water separator tank and drain if necessary.

- Vapor System:

  Check all piping and connections to the vapor and groundwater treatment systems for any signs of leaks, damage, or corrosion.

In addition to the general procedures outlined above, the data sheet which follows should be completed at least once each week.

SVE/BV System - Vapor Data Sheet

Date: __________
Time: __________
Operator: __________

Pressure Readings

Atmospheric Pressure (mm Hg.): __________
Vacuum at Extraction Well Head (cm H_2O): __________
Vacuum at Blower Intake (cm H_2O): __________
Pressure at Blower Discharge (cm H_2O): __________
Pressure at Carbon Midpoint (cm H_2O): __________
Vacuum at Monitoring Well 1 (cm H_2O): __________
Vacuum at Monitoring Well 2 (cm H_2O): __________
Vacuum at Monitoring Well 3 (cm H_2O): __________
Vacuum at Monitoring Well 4 (cm H_2O): __________

Temperature Readings

Ambient Temperature (°K): __________
Vapor Temperature at Wellhead (°K): __________
Temperature at Blower Discharge (°K): __________
Temperature at Carbon Effluent (°K): __________

Flow Readings

Well Head Flow Rate (acmm): __________
Blower Inlet Flow Rate (acmm): __________
Carbon Effluent Flow Rate (acmm): __________

Total VOC Readings

Well Head (ppm): __________
Carbon Influent (ppm): __________
Carbon Midpoint (ppm): __________
Carbon Effluent (ppm): __________

Other Measurements

Oxygen and Carbon Dioxide Concentrations and Respiration Rates __________
Relative Humidity of Influent Vapor Stream (%): __________
Blower Amperage (amps): __________
Condensate Collection Tank Level (m) __________
Water Table Elevations (m below ground surface) __________

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

Shutdown of a remediation system is driven either by Federal and state regulatory cleanup requirements or voluntary cleanup requirements established for the particular contaminant(s) to be remediated. Site-specific cleanup objectives are usually established by the Federal and/or state agencies, if no generic cleanup levels exist. Sometimes regulators require that the contaminant(s) be remediated to nondetect levels. 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.

9-3. Sampling

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 Analysis/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.

9-4. Analytical

Standard laboratory analyses are usually required at this stage. Use of standard reference materials to enhance comparability of data over time and across laboratories will make the comparison valid.

a. 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.

b. Completion of remediation will be documented by attainment of agreed-upon contaminant concentrations using agreed-upon sampling and analysis methodologies. For sites contaminated by fuel products rather than specific solvents, compositional makeup may be a determining factor in deciding that cleanup is finished. By monitoring the weathering of fuels, it may be found that the lighter, more mobile, more toxic compounds have degraded, leaving less toxic, less mobile components behind. This type of endpoint must also have been agreed upon before the start-up phase of the project.

9-5. Evaluation of Results

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.
- Extraction well(s) vapor concentrations.
- Extraction well(s) vapor composition.
- Soil gas contaminant concentrations and composition.
- Residual soil concentrations.

a. As discussed above, most states' target cleanup levels 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

Table 9-1
Factors Influencing Shutdown of SVE/BV System

Offgas Analysis (Continuous and Pulse Venting)
• Total hydrocarbon emissions or individual VOCs exiting blower exhaust are not evident.
• Total hydrocarbon emissions or individual VOCs exiting blower exhaust reach predetermined levels (operator's decision).
• Total hydrocarbon emissions or individual VOCs exiting blower exhaust reach asymptotic conditions.
• Operation costs greatly exceed rate of removal (operator's decision).
• Pulse venting down time greatly exceeds pulse venting operation time (operator's decision).
• Oxygen respiration measurements performed within the area being remediated indicate declining contaminant degradability, relative to a background control.
Soil Gas Analysis
• Soil gas constituents collected from the area being remediated reach asymptotic conditions.
• Soil gas constituents collected from the area being remediated indicate levels of nondetection.
Soil Sample Analysis
• Soil constituents collected from the area being remediated indicated levels below regulatory requirements or levels of nondetection (confirmatory analyses).
Other
• 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 acting regulatory agency to accept remediated levels (refer to paragraph 9-5, Evaluation of Results).

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 extracted vapor concentration, 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 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.

b. 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 concentrations of VOC are measured in the initial airstream to the pump and are 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.

c. There are some caveats to these methods, however. First, although the decrease of concentrations in the extracted vapor is a good indication of the effectiveness of the system, it is not necessarily 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.

d. Because of this uncertainty, the composition of the extracted vapors is usually monitored as well as the concentrations. A change in composition, typically toward heavier, less volatile constituents, accompanied by a decrease in overall concentration, is a good indication of a reduction in soil concentrations. When these heavier constituents become the predominant fraction of the extracted vapor, it signals that the lighter, more mobile constituents have been removed.

e. 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.

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 reason 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.
- 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 advect clean air through the entire system.
- Shut down vacuum pump(s) or extraction blower(s).
- 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. 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, 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. Examples of 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. 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 2-3*c*(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. Concentrations of contaminants in water should also be monitored to determine the contribution of contaminants from the aqueous phase to the soil gas. Residual phase analyses can indicate the presence of a continuing source of contamination. 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 that 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).

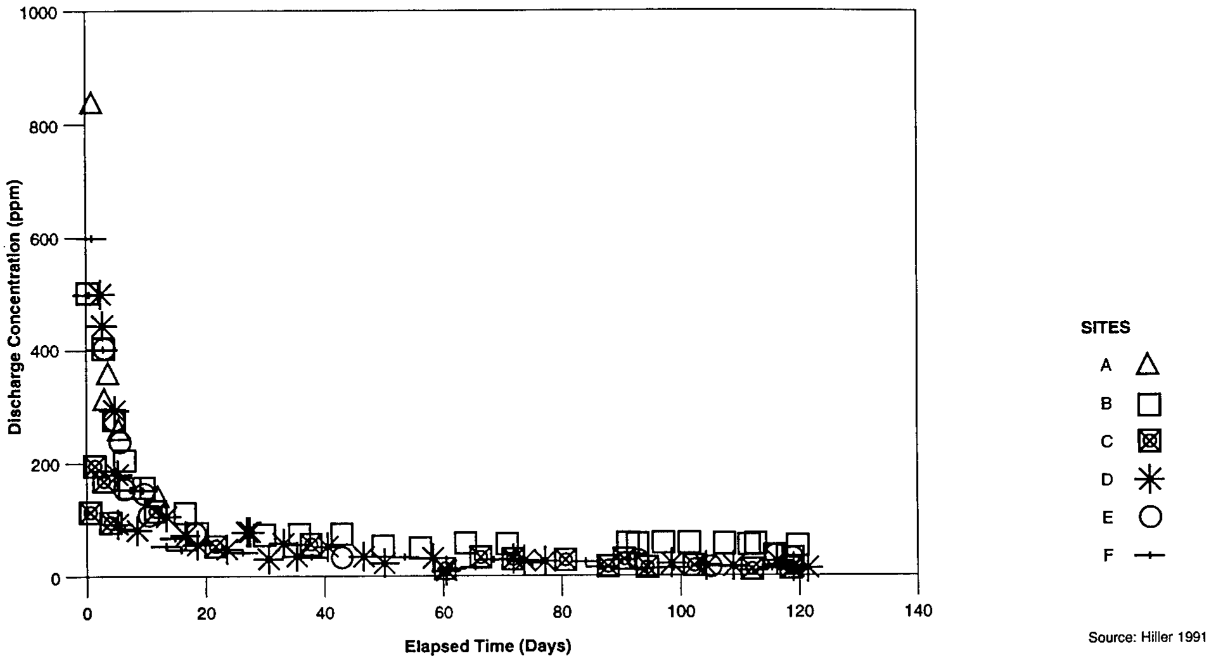
d. Air, being a mixed medium, is more economical than soil for monitoring the progress of SVE/BV operations. Vent gas concentrations can provide a gauge of mass removal from the whole soil volume affected by the SVE/BV system, while soil gas monitoring can resolve spatial variation in vapor phase contaminant concentrations. Monitoring of vapor phase compounds 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.

e. BV is at times employed for aboveground 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 increasingly more slowly over time. Concurrent shutdown testing performed periodically indicated that oxygen uptake rates declined over time, signalling 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).

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.

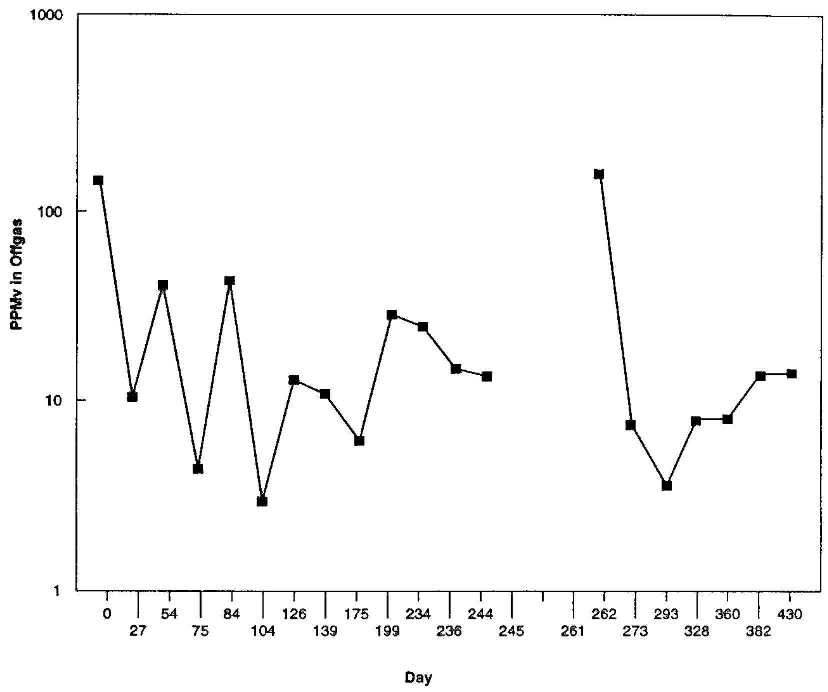
g. When subsurface contaminant transport is limited by diffusion, desorption, or partitioning, SVE vent gas concentrations can appear deceptively low even when significant contamination remains in the nonvapor phases. In some cases, low concentrations may simply mean that venting flow rates are higher than necessary. Soil gas contaminant concentrations are typically monitored after SVE system shutdown to detect rebound which could be caused by these other transport processes. Rebounding concentrations imply that a contamination source is still present.

h. As described in paragraph 9-5, pulsed venting produces VOC data trends in the vent gas which can be analyzed by tracking the initial peak values when an area is restored to vacuum conditions. Figure 9-2 illustrates this; the "rebound" peaks trend downward, as expected, but do so at a slower pace than if the area had been under vacuum continuously. This does not necessarily mean that the remediation has been prolonged, because the vent gas concentration is higher than it would have been if the area had been under vacuum continuously.



Source: Hiller 1991

Figure 9-1. Vent gas VOC concentrations at six sites over time



Source: Data from ETG Environmental, Inc. 1994

Figure 9-2. Example of rebounding at a site

i. If continuous venting is used, the system will usually be shut down for a period of up to two weeks, and the vent gas concentration will be rechecked. If it has rebounded above the agreed action level, the system must be operated until the vent gas concentration falls below the action level. This process may be repeated several times before the rebound concentration stabilizes at an acceptable level for shutdown to occur.

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, 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) provides a standard structure for categorizing and reporting costs. Remedial action cost estimates must be categorized by using the most current approved HTRW RA-WBS.

c. List cost components. A list of cost components should be prepared. Components common to SVE/BC 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.

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 equipment. The goal of the estimate affects the method and level of detail of analysis. A detailed discussion of finance is beyond the scope of this 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.

Table 10-1
Suggested Cost Estimating Checklist (Continued)

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)

Table 10-1
(Continued)

Treatment System Capital Components

Major Components

Air/Water Separator
Condensate Drop-Out Tank
Blower
Silencers
Air Filters
Carbon Vessels
Fume Incinerator
    Burner
    Catalyst
    Heat Exchanger
VOC Monitor
O_2/CO_2 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

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

Net Present Worth For Annual O&M

(Sheet 2 of 3)

Table 10-1
(Concluded)

Shutdown

Final Sampling
Regulatory Interactions
Equipment Disassembly and Demobilization
Demolition
Salvage Value Credit (Negative Cost)
Reporting

(Sheet 3 of 3)

Chapter 11
Other Considerations

11-1. Regulatory Issues

State and Federal regulatory requirements should be identified by the designer prior to 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 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.

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 1-4*f*). (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.

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.

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 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 stringent. 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 stringent* of the regulations shall apply.

a. The SSHP monitoring provisions shall include work area monitoring for the presence of explosive 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 sites such as, but not necessarily limited to, noise protection (especially around the blowers), adequate ventilation (for indoor blower housings), and temperature extremes (especially during periods of extremely hot or cold weather).

11-4. Contracting

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.

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

Department of the Army

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 1110-3-1301
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 1110-345-710
Drawings

ER 1110-345-720
Construction Specifications

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

CE-15995
Commissioning of HVAC Systems

U.S. Environmental Protection Agency

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USEPA 1993d
USEPA. 1993d. *Presumptive Remedies Site Characterization and Technology Selection for CERCLA Sites with VOCs in Soils*. EPA/540/F-93/048.

USEPA 1995
USEPA. 1995. *Guide to Documenting Cost and Performance for Remediation Projects*, EPA-542-B95-002, Member Agencies of the Federal Remediation Technologies Roundtable, March 1995. 55 pp.

American National Standards Institute (ANSI)

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
Test Code for the Measurement of Sound from Pneumatic Equipment

MSS SP-58,-69,-89,-90

American Petroleum Institute (API)

API-650
Field Erected Tanks

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

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

Z501 Design Guide

Institute of Electrical and Electronics Engineers (IEEE)

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
Shop Fabricated Aboveground Tanks

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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 diaromatics.

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.

Table B-1
Selected Compounds and Their Chemical Properties

Compound	M_w (g/mole)	T_b (1 atm) (K)	P_v^o (K) (atm)	C_{est} (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_w - molecular weight.
T_b(1 atm) - compound boiling point at 1 atm absolute pressure.
P_v^o (293 K), - vapor pressure measured at 293 K.
C_{est} - equilibrium vapor concentration.

dec. - decomposes

Johnson, Kemblowski, and Colthart (1988). "Practical screening models for soil venting applications." In: *Proceedings of NWWA/API; Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater.* Houston, TX. Reprinted by permission of NGWA.

Table B-2
Physiochemical Properties of PCE and Associated Compounds*

Formula	**PCE** C_2Cl_4	**TCE** C_2HCl_3	**1,1-DCE** $C_2H_2Cl_2$	**t-1,2-DCE** $C_2H_2Cl_2$	**c-1,2-DCE** $C_2H_2Cl_2$	**V C** C_2H_3Cl
Molecular weight (g/mol)	165.85	131.40	96.95	96.95	96.95	62.5
Liquid density (g/cm^3)	1.625	1.46	1.214	1.257	1.284	0.9121#
Melting point (K)	250.6	200	150.4	223.6	191.5	119.2
Boiling point (K)	394	360	304.6	320.7	333.2	259.6
Vapor pressure (mmHg)	14	$69^{\circ 1}$	500	5.3	2.7	2300
Water solubility (mg/l)	150	1100^1	400	6300	3500	1100
Log octanol - water coefficient	3.14	2.42	2.13	2.09	1.86	1.23
Soil sorption coefficient (l/kg)	665	NA	65	59	35	8.2
Henry's Law constant (atm. m^3/mol)	0.023	$.0103^1$	0.154	0.0066^1	0.0075^1	0.695

*All values are at 293 K, unless otherwise indicated.
#Value is a specific gravity measurement.
[1] At 298 K.
NA = information not available.

Arthur D. Little, Inc. (1987). *The installation restoration program toxicology guide, Volume 1.* Section 2:1-16.

Table B-3
Physiochemical Properties of TCA and Associated Compounds*

Formula	**1,1,1-TCA** $C_2H_3Cl_3$	**1,1-DCA** $C_2H_4Cl_2$	**CA** C_2H_5Cl
Molecular weight (g/mol)	133.42	98.97	64.52
Liquid density (kg/m^3)	1.325	1.175	0.921[1]
Melting point (K)	240	176.3	132.15
Boiling point (K)	347	330.3	285.5
Vapor pressure (mmHg)	100	182	1000
Water solubility (mg/l)	950	5500	5700
Log octanol - water coefficient (l/kg)	2.49	1.79	1.43
Soil sorption coefficient (l/kg)	152	30	14.9
Henry's Law constant (atm. m^3/mol)	0.0276[2]	0.0057[2]	0.011

*All values are at 293 K, unless otherwise indicated.
[1] At 273 K
[2] At 298 K

Arthur D. Little, Inc. (1987). *The installation restoration program toxicology guide, Volume 1.* Section 2:1-16.

Table B-4
Physical Properties of Fuel Components (Continued)

Component	MW	Solubility	Koc	Log Kow	VP	References
n-Alkanes n-Butane	58.12	61			1555.33	////A
n-Decane	142.28	0.009 (20)			2.7	/B///B
n-Dodecane	170.33	0.0037	5500000	7.06	0.3	/A/C/C/A
n-Hexane	86.18	9.5	3830	3.9	121.24	/D/C/C/A
n-Heptane	100.20	2.4 (20)			35.55	/B///A
n-Nonane	128.25	0.07 (20)			3.22	/B///B
n-Octane	114.23	0.0657	73000	4.00	10.46	/E/C/E/A
n-Pentane	72.15	38.5			424.38	/D///A
n-Tridecane	184.35	0.013				/B///
n-Undecane	156.31				1 (32.7)	////B
Isoalkanes 2-Methyldecane	156.31					////
2-Methylhexane	100.20				51.9	////A
2-Methylpentane	86.18	13.8			171.5	/D///A
2,4-Dimethylhexane	114.23				23.32	////A
2,5-Dimethylhexane	114.23					////
2,2,3-Trimethylpentane	114.23		36000	4.87		//C/C/
2,2,4-Trimethylpentane	114.23	0.56	36000	5.02		/B/C/E/
3-Methylhexane	100.20					////
3-Methylpentane	86.18		3830	3.9		//C/C/
3,4-Dimethyloctane	142.28					////
4-Methylheptane	114.23					////
Isobutane	58.12	48.9			2252.75	/D///A
Isododecane	170.33					////
Isopentane	72.15	47.7	900	2.3	574.89	/E/C/E/A
Isoundecane	156.31					////
Cycloalkanes 1,3,5-Trimethylcyclohexane	126.24		50500	5.02		//C/C/
Cyclohexane	84.16	55.6	1330	3.44	77.55	/E/C/E/A
Methylcyclohexane	98.19	14 (20)	6070	4.1	144	//C/C/B
Methylcyclopentane	83.15	42.7	1400	2.35		/E/C/E/
Alkenes trans-2-Butene	56.11				760 (0.9)	////B
2-Methyl-2-butene	70.13					////

**Table B-4
(Concluded)**

Component	MW	Solubility	Koc	Log Kow	VP	References
Aromatics 1-Methyl-3-ethylbenzene	120.19					////
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
PAHs 1-Methylnaphthalene	142.20	27	3570	3.87		B/B/C/C/
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. Verschueren (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[a]

			Military[b]			
	Civil ASTM D 1655		Mil-T-5624-K		Mil-T-38219	Mil-T-83133
Characteristic	**Jet A kerosene**	**Jet B wide-cut**	**JP-4 wide-cut USAF**	**JP-5 kerosene USN**	**JP-7[c] kerosene USAF**	**JP-8 kerosene USAF**
Composition						
aromatics, vol. % max	20[d]	20[d]	25	25	5	25
sulfur, wt % max	0.3	0.3	0.4	0.4	0.1	0.4
Volatility						
distillation-10% received	204			205	196	205
temperature-50% received		188	190			
max k-endpoint	573		543	563	561	573
vapour pressure at 311 K kPa max (psi)		21(3)	14-21(2-3)			
density at 288 K, kg/m^3	775-840	751-802	751-802	788-845	779-806	775-840
Fluidity						
freezing-point, k max	233[e]	223	215	227	230	223
viscosity at 253 K, mm^3/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[f]	20[f]	20	19	35[c]	20
H_2 content, wt % min			13.6	13.5	14.2[c]	13.6

Note:

[a] From Dukek (1978); full specification requires other tests.
[b] USAF, US Air Force; USN, US Navy
[c] Estimated properties for advanced supersonic fuel
[d] Fuel up to 25 vol % aromatics may be supplied on notification (22 vol % for Jet A-1, Jet B).
[e] International airlines use Jet A-1 with 223 k freeze-point.
[f] 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.

Table B-6
Detectable Hydrocarbons Found in U.S. Finished Gasolines at a Concentration of 1% or More[a]

Chemical	Weight %	
	Estimated Range	Weighted Average[b]
Toluene	5-22	10
2-Methylpentane + 4-Methyl-cis-2-pentene + 3-Methyl-cis-2-pentene[c]	4-14	9
n-Butane	3-12	7
iso-Pentane	5-10	7
n-Pentane	1-9	5
Xylene (three isomers)	1-10	3
2,2,4-Trimethylpentane	<1-8	3
n-Hexane	<1-6	2
n-Heptane	<1-5	2
2,3,3-Trimethylpentane	<1-5	2
2,3,4-Trimethylpentane	<1-5	2
3-Methylpentane	<1-5	2
Methylcyclohexane + 1-cis-2-Dimethylcyclopentane + 3-Methylhexane[c]	<1-5	1
Benzene	<1-4	2
2,2,3-Trimethylpentane	<1-4	2
Methyl tertiary butyl ether	<1-4	1
Methylcyclopentane	<1-3	2
2,4-Dimethylpentane	<1-3	1
Cyclohexane	<1-3	1
1,2,4-Trimethylbenzene	<1-3	1
2-Methyl-2-butene	<1-2	2
2,3-Dimethylbutane	<1-2	1
trans-2-Pentene	<1-2	1
Methylcyclohexane	<1-2	1
3-Ethyltoluene	<1-2	1
2,3-Dimethylpentane	<1-2	1
2,5-Dimethylpentane	<1-2	1
2-Methyl-1-butene	<1-2	1
Ethyl benzene	<1-2	1

[a] Provided by American Petroleum Institute
[b] The sum of the weighted average does not equal 100% because numerous components were detected at less than 1%.
[c] These chemicals could not be distinguished by gas chromatography because of similar retention times.

World Health Organization, International Agency for Research on Cancer. (1989). "IARC monographs on the evaluation of carcinogenic risks to humans - occupational exposures in petroleum refining; crude oil and major petroleum fuels." Volume 45. *IRAC*, Lyon, France.

Table B-7
Major Component Streams of European Automotive Diesel Oil (Diesel Fuel No. 2) and Distillate Marine Diesel Fuel (Diesel Fuel No. 4)[a]

Toxic Substances Control Act (TSCA) Inventory Name and Identification Number[b]	Refinery Process Stream (nomenclature used in Europe)	Automotive Diesel Oil (vol. %)	Distillate Marine Diesel Fuel (vol. %)
	Straight-run (atmospheric) gas oil		
Straight-run middle distillate [6]	- light	40-100	40-100
Straight-run gas oil [7]	- heavy	0-3	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

[a] From CONCAWE (1985).

[b] 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). "IARC monographs on the evaluation of carcinogenic risks to humans - occupational exposures in petroleum refining; crude oil and major petroleum fuels." Volume 45. *IRAC*, Lyon, France.

Table B-8
Henry's Law Constants (H, atm-m^3/mol) for Selected Organic Compounds [Data Obtained from Mabey et al. (1982) and Mackay and Shiu (1981)] (Continued)

Compound	H	t (K)^a	Compound	H	t (K)^a
Chlorinated Nonaromatics			Monocyclic Aromatics		
			Polycyclic Aromatics		
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	Pesticide and Related Compounds, and PCBs		
Tetrachloroethene	0.0153	293	Ethylene dibromide (EDB)^b	0.00082	298
1,2-Dichloropropane	0.0023	293	trans-Chlordane	0.000094	298
trans-1,3-Dichloropropene	0.0013	293/298	Heptachlor	0.0040	298

**Table B-8
(Concluded)**

Hexachlorocyclopentadiene	0.016	298	Heptachlor epoxide	0.00039	298
Hexachlorobutadiene	0.026	293	2,3,7,8-TCDD	0.0021	--
Chlorinated Ethers			Aroclor 1016[c]	0.00033	298
Bis(chloromethyl)ether	0.00021	293/298	Aroclor 1221[c]	0.00017	298
Bis(2-chloroisopropyl)ether	0.00011	293	Aroclor 1242[c]	0.0020	298
4-Chlorophenylphenylether	0.00022	293	Aroclor 1248[c]	0.0036	298
4-Bromophenylphenylether	0.00010	293/298	Aroclor 1254[c]	0.0026	--

[a] Where two temperatures are given, the first is the temperature at which the vapor pressure was measured, and the second is the temperature at which the solubility was measured.

[b] Vapor pressure data from Stull (1947), and solubility data from Stephen and Stephen (1963).

[c] 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.

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^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days)
										Low High
Alcohols										
Ethyl alcohol	46.07	280,000	0.789	59	1.2E-05	0.12368	0.3	3.1	0.34	
Methyl alcohol	32	300,000		130	2.0E-05	0.16211	0.1	1.5	2.3	
t-Butyl alcohol	74.1		0.788	42		0.09752		0.37		
Cycloalkanes										
Cyclopentane	70.14	160	0.751	42.4	1.9E+01					
Methyl cyclohexane	98.19	14	0.77	6.18	4.3E+01					
Cycloalkenes										
Cyclohexene	84.16	55 (20°C)	0.779							
Cyclopentene	68.12		0.77	77 (20°C)						
Chlorinated Aliphatics										
1,2-Dichloroethane	99	7,986-8,650	1.23	87	1.3E-03	0.09451	65	1.48-2.13	5.6	28-180
Dibromoethane	187.88	4.32 (30°C)	2.701	17 (30°C)						
1,1-Dichloroethane	99	5,060	1.1757	182.1	5.9E-03	0.0959	30.2	1.79		
Ether										
Methyl-t-butyl ether	88	4,800	0.74	250	5.9E-03	0.10172	41	1.2	1.5	28-180
Ketone										
Methyl isobutyl ketone	100.2	20,400	0.8017	14.5	9.4E-05	0.07588	19 to 106	1.19		
Methyl Alkanes										
2,3-Dimethylbutane	86.7	19.1		31.3	1.3E+02					
2,3-Dimethylpentane	100.21	5.25		9.18	1.8E+02					

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^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days)	
										Low	High
2,4-Dimethylpentane	100.21	5.5		13.1	3.0E+02						
3,3-Dimethylpentane	100.21	5.94		11	1.9E+02						
2-Methylheptane	114.23										
3-Methylheptane	114.23	0.792		2.6	3.8E+02						
4-Methylheptane	114.23										
2-Methylhexane	100.21	2.54		8.78	3.5E+02						
3-Methylhexane	100.21	4.95		8.21	2.4E+02						
4-Methyloctane	128.26	0.115		0.903	1.0E+03						
2-Methylpentane	86.17	13	0.654	28.2	1.7E+02						
3-Methylpentane	86.17	13.1	0.6645	25.3	1.7E+02						
2,2,4-Trimethylhexane	128.26										
2,2,5-Trimethylhexane	128.26	1.15		2.21	3.5E+02						
2,3,3-Trimethylhexane	128.26										
2,3,5-Trimethylhexane	128.26										
2,4,4-Trimethylhexane	128.26										
2,2,3-Trimethylpentane	114.23										
2,2,4-Trimethylpentane	114.23	2.44		6.56	3.3E+02						
2,3,3-Trimethylpentane	114.23										
2,3,4-Trimethylpentane	114.23	2.3		3.6	1.9E+02						
Methyl Alkenes											
2-Methyl-1-butene	70.14		0.65								
2-Methyl-2-butene	70.14		0.668								

Table 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^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days)
										Low High
3-Methyl-1-butene	70.14	130	0.648	120	5.5E+01					
2-Methyl-1-pentene	86.16	78	0.6817							
2-Methyl-2-pentene	86.16									
3-Methyl-cis-2-pentene	86.16									
3-Methyl-trans-2-pentene	86.16			0.67						
4-Methyl-cis-2-pentene	86.16			0.67						
4-Methyl-trans-2-pentene	86.16									
Monocyclic Aromatic Hydrocarbons										
Benzene	78	1.780	0.88	95	5.5E-03	9.30E-02	49 to 100	1.56 to 2.15	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			

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^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days) Low High
Propylbenzene	120.2	60		0.449	7.0E-1					
n-Propylbenzene	120	60 (15C)	0.862	2.5 (20°C)	5.6E-03 (15°C)			3.57 to 3.68		
1,2,3,4-Tetramethylbenzene	215.9	4.31		0.00876	2.6E-01		1,500			
1,2,3,5-Tetramethylbenzene	215.9	3.5		0.0186	5.9E-01		1,500			
1,2,4,5-Tetramethylbenzene	134.2	3.48		0.0659	2.5E+00		1,500			
Toluene	92	490 to 627	0.87	28	6.7E-03	7.80E-02	115 to 150	2.11 to 2.8	10.7	4
1,2,3-Trimethylbenzene	120						884			
1,2,4-Trimethylbenzene	120	57 (20°C)	0.88	1.4	3.9E-01 (20°C)		1,600	3.4	230	7
1,3,5-Trimethylbenzene	120	64	0.865	1.4	3.7E-01	1.60E+02	3.4	230		
m-Xylene	106	173	0.8684	10	6.3E-03		1,585	3.2		
o-Xylene	106	204	0.87596	10	5.4E-03		129	2.77 to 3.16		
p-Xylene	106	200	0.85665	10	6.3E-03		204	3.15		
Xylenes	106	162 to 200	0.87	6.6 to 8.8	6.3E-03	7.20E-02	128 to 1,580	2.77 to 3.2	132	7
Polycyclic Aromatic Hydrocarbons										
Anthracene	178	0.030 to 0.1125	1.24	1.7E-05 to 1.95E-4	6.5E-05	5.90E-02	16,000 to 26,000	4.34 to 4.54	30	0.071/0.024
Benzo(a)pyrene	252	0.0038 to 0.004	1.35	5.5E-09	<2.4E-6	4.70E-02	398,000 to 1,900,000	5.81 to 6.50	30	0.015/0.046
Benzo(b)fluoranthene	252	0.0012	ND	5.0E-07	1.2E-05	4.40E-02	550,000	6.57	ND	0.36
Benzo(e)pyrene	252					4.70E-02				

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^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days) Low High
1,2-Dimethylnaphthalene	158						4,230			
1,3-Dimethylnaphthalene	158						4,230			
Fluoranthene	202	0.206 to 0.373	1.25	0.000005	1.7E-02	4.2E-02	5.22	1,150	0.875	2.6
Fluorene	166	1.66 to 1.98	1.2	1E-3 to 1E-2	2.1E-04	5.70E-02	5,000	4.12 to 4.38	30	32
Methylnaphthalene	142	27								
1-Methylnaphthalene	142	28	1.025	ND	ND	ND	ND	ND	129	ND
2-Methylnaphthalene	142	25	1.001	0.045	3.4E-04	6.20E-02	7,400 to 8,500	3.86 to 4.11	190	ND
Naphthalene	128	30 to 34	1.16	2.3E-1 to 8.7E-1	4.6E-04	8.20E-02	550 to 3,160	3.2 to 4.7	10.5	0.5
Phenanthrene	178	0.71 to 1.29	1.18	0.00068	2.6E-05	5.40E-02	5,250 to 38,900	4.2 to 4.6	30	0.125/1.04
Pyrene	202	0.013 to 0.171	1.27	6.85E-07 to 2.5E-06	1.1E-05	5.00E-02	46,000 to 135,000	4.88 to 5.32	30	0.028/0.085
Simple Alkanes										
n-Butane	58.13	61	0.6	1.82E+03	9.6E-01					
Decane	148.28	0.008								
n-Decane	148.28	0.052		1.31	7.0E+00					
Dodecane	170.33	0.0037		0.0118	7.5E+00					
n-Dodecane	170.33									
n-Eicosane	282.6	0.0019		2.67E-06	2.9E-01					
n-Heptane	100.21	3		0.515	2.3E+00					
n-Hexadecane	226.44	0.00628		0.00917	2.3E+01					

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^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days)	
										Low	High
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										

Table B-9
(Concluded)

Constituents	Molecular Weight	Water Solubility mg/L 298 K	Specific Gravity	Vapor Pressure mm Hg 298 K	Henry's Law Constant atm-m^3/mol 298 K	Diffusivity cm^2/sec	K_{oc} mL/g	Log K_{ow}	Fish BCF L/kg	Surface-Water $T_{1/2}$ (days)	
										Low	High
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
$T_{1/2}$ - 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 (Continued)

Component	283 K	289 K	293 K	298 K	303 K
Nonane	17.21519	20.97643	13.80119	16.92131	18.69235
n-Hexane	10.24304	17.46626	36.70619	31.39026	62.70981
2-Methylpentane	29.99747	29.35008	26.31372	33.72000	34.08841
Cyclohexane	4.43291	5.32869	5.81978	7.23447	8.96429
Chlorobenzene	0.10501	0.11884	0.14175	0.14714	0.19014
1,2-Dichlorobenzene	0.07015	0.06048	0.06984	0.06417	0.09527
1,3-Dichlorobenzene	0.09511	0.09769	0.12222	0.11649	0.16964
1,4-Dichlorobenzene	0.09124	0.09177	0.10767	0.12957	0.15637
o-Xylene	0.12266	0.15267	0.19704	0.19905	0.25164
p-Xylene	0.18076	0.20427	0.26813	0.30409	0.37988
m-Xylene	0.17689	0.20976	0.24859	0.30409	0.35656
Propylbenzene	0.24446	0.30915	0.36623	0.44143	0.55072
Ethylbenzene	0.14030	0.19073	0.24983	0.32208	0.42209
Toluene	0.16397	0.20807	0.23071	0.26240	0.32480
Benzene	0.14203	0.16409	0.18790	0.21581	0.28943
Methylethylbenzene	0.15106	0.17762	0.20910	0.22807	0.30953
1,1-Dichloroethane	0.15838	0.19200	0.23404	0.25545	0.31194
1,2-Dichloroethane	0.05035	0.05498	0.06111	0.05763	0.06995
1,1,1-Trichloroethane	0.41532	0.48635	0.60692	0.71119	0.84819
1,1,2-Trichloroethane	0.01678	0.02664	0.03076	0.03719	0.05346
cis-1,2-Dichloroethylene	0.11620	0.13787	0.14965	0.18556	0.23114
trans-1,2-Dichloroethylene	0.25390	0.29815	0.35625	0.38625	0.48640
Tetrachloroethylene	0.36410	0.46943	0.58614	0.69892	0.98487
Trichloroethylene	0.23154	0.28208	0.35002	0.41690	0.51454
Tetralin	0.03228	0.04441	0.05654	0.07643	0.10773
Decalin	3.01266	3.53977	4.40641	4.78211	7.99952
Vinyl chloride	0.64557	0.71049	0.90207	1.08313	1.12556
Chloroethane	0.32666	0.40515	0.45727	0.49456	0.57484
Hexachloroethane	0.25522	0.23641	0.24568	0.34129	0.41405
Carbon tetrachloride	0.63696	0.80776	0.96442	1.20575	1.51951
1,3,5-Trimethylbenzene	0.17344	0.19454	0.23736	0.27507	0.38711
Ethylene dibromide	0.01291	0.02030	0.02536	0.02657	0.03216
1,1-Dichloroethylene	0.66278	0.85851	0.90622	1.05860	1.27832

Table B-10
(Concluded)

Component	283 K	289 K	293 K	298 K	303 K
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)).

Table B-11
Chemical Properties of Hydrocarbon Constituents

Chemical Class	Representative Chemical	Liquid Density (g/cm^3) @ 293 K	Henry's Law Constant (dim.)	Water Solubility (mg/L) @ 298 K	Pure Vapor Pressure (mm Hg) @ 293 K	Vapor Density (g/m^3) @ 293 K	Soil Sorption Constant (K_{oc}) (L/kg) @ 298 K
n-Alkanes							
C4	n-Butane	0.579	25.22	61.1	1560	4960	250
C5	n-Pentane	0.626	29.77	41.2	424	1670	320
C6	n-Hexane	0.659	36.61	12.5	121	570	600
C7	n-Heptane	0.684	44.60	2.68	35.6	195	1300
C8	n-Octane	0.703	52.00	0.66	10.5	65.6	2600
C9	n-Nonane	0.718	NA	0.122	3.2	22.4	5800
C10	n-Decane	0.730	NA	0.022	0.95	7.4	13000
Mono-aromatics							
C6	Benzene	0.885	0.11	1780	75.2	321	38
C7	Toluene	0.867	0.13	515	21.8	110	90
C8	m-Xylene	0.864	0.12	162	6.16	35.8	220
C8	Ethylbenzene	0.867	0.14	167	7.08	41.1	210
C9	1,3,5-Trimethylbenzene	0.865	0.09	72.6	1.73	11.4	390
C10	1,4-Diethylbenzene	0.862	0.19	15	0.697	5.12	1100
Phenols							
Phenol	Phenol	1.058	0.038	82000	0.529	2.72	110
C1-Phenols	m-Cresol	1.027	0.044	23500	0.15	0.89	8.4
C2-Phenols	2,4-Dimethylphenol	0.965	0.048	1600	0.058	0.39	NA
C3-Phenols	2,4,6-Trimethylphenol	NA	NA	NA	0.012	0.09	NA
C4-Phenols	m-Ethylphenol	1.037	NA	NA	0.08	0.53	NA
Indanol	Indanol	NA	NA	NA	0.014	0.1	NA
Di-aromatics	Naphthalene	1.025	NA	30	0.053	0.37	690

Note: NA - Not available
dim. - dimensionless

Source: USEPA (1991d).

Table B-12
Composition of a Regular Gasoline (Continued)

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial	
			Mass Fraction	Mole Fraction
Propane	C_3H_8	44.1	0.0001	0.0002
Isobutane	C_4H_{10}	58.1	0.0122	0.1999
n-Butane	C_4H_{10}	58.1	0.0629	0.1031
trans-2-Butene	C_4H_{10}	56.1	0.0007	0.0012
cis-2-Butene	C_4H_{10}	56.1	0.0000	0.0000
3-Methyl-1-butene	C_5H_{10}	70.1	0.0006	0.0008
Isopentane	C_5H_{12}	72.2	0.1049	0.1384
1-Pentene	C_5H_{10}	70.1	0.0000	0.0000
2-Methyl-1-butene	C_5H_{10}	70.1	0.0000	0.0000
2-Methyl-1,3-butadiene	C_5H_8	68.1	0.0000	0.0000
n-Pentane	C_5H_{12}	72.2	0.0586	0.0773
trans-2-Pentene	C_5H_{10}	70.1	0.0000	0.0000
2-Methyl-2-butene	C_5H_{10}	70.1	0.0044	0.0060
3-Methyl-1,2-butadiene	C_5H_8	68.1	0.0000	0.0000
3,3-Dimethyl-1-butene	C_6H_{12}	84.2	0.0049	0.0055
Cyclopentane	C_5H_{10}	70.1	0.0000	0.0000
3-Methyl-1-pentene	C_6H_{12}	84.2	0.0000	0.0000
2,3-Dimethylbutane	C_6H_{14}	86.2	0.0730	0.0807
2-Methylpentane	C_6H_{14}	86.2	0.0273	0.0302
3-Methylpentane	C_6H_{14}	86.2	0.0000	0.0000
n-Hexane	C_6H_{14}	86.2	0.0283	0.0313
Methylcyclopentane	C_6H_{12}	84.2	0.0000	0.0000
2,2-Dimethylpentane	C_7H_{16}	100.2	0.0076	0.0093
Benzene	C_6H_6	78.1	0.0076	0.0093
Cyclohexane	C_6H_{12}	84.2	0.0000	0.0000
2,3-Dimethylpentane	C_7H_{16}	100.2	0.0390	0.0371
3-Methylhexane	C_7H_{16}	100.2	0.0000	0.0000
3-Ethylpentane	C_7H_{16}	100.2	0.0000	0.0000
2,2,4-Trimethylpentane	C_8H_{18}	114.2	0.0121	0.0101
n-Heptane	C_7H_{16}	100.2	0.0063	0.0060
Methylcyclohexane	C_7H_{14}	98.2	0.0000	0.0000
2,2-Dimethylhexane	C_8H_{18}	114.2	0.0055	0.0046

Table B-12
(Concluded)

			Initial	
Component Number	**Chemical Formula**	$M_{w,i}$ **(g)**	**Mass Fraction**	**Mole Fraction**
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 (Continued)

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial Mass Fraction	Initial Mole Fraction
Propane	C_3H_8	44.1	0.0000	0.0000
Isobutane	C_4H_{10}	58.1	0.0000	0.0000
n-Butane	C_4H_{10}	58.1	0.0000	0.0000
trans-2-Butene	C_4H_8	56.1	0.0000	0.0000
cis-2-Butene	C_4H_8	56.1	0.0000	0.0000
3-Methyl-1-butene	C_5H_{10}	70.1	0.0000	0.0000
Isopentane	C_5H_{12}	72.2	0.0200	0.0290
1-Pentene	C_5H_{10}	70.1	0.0000	0.0000
2-Methyl-1-butene	C_5H_{10}	70.1	0.0000	0.0000
2-Methyl-1,3-butadiene	C_5H_8	68.1	0.0000	0.0000
n-Pentane	C_5H_{12}	72.2	0.0114	0.0169
trans-2-Pentene	C_5H_{10}	70.1	0.0000	0.0000
2-Methyl-2-butene	C_5H_{10}	70.1	0.0000	0.0000
3-Methyl-1,2-butadiene	C_5H_8	68.1	0.0000	0.0000
3,3-Dimethyl-1-butene	C_6H_{12}	84.2	0.0000	0.0000
Cyclopentane	C_5H_{10}	70.1	0.0000	0.0000
3-Methyl-1-pentene	C_6H_{12}	84.2	0.0000	0.0000
2,3-Dimethylbutane	C_6H_{14}	86.2	0.0600	0.0744
2-Methylpentane	C_6H_{14}	86.2	0.0000	0.0000
3-Methylpentane	C_6H_{14}	86.2	0.0000	0.0000
n-Hexane	C_6H_{14}	86.2	0.0370	0.0459
Methylcyclopentane	C_6H_{12}	84.2	0.0000	0.0000
2,2-Dimethylpentane	C_7H_{16}	100.2	0.0000	0.0000
Benzene	C_6H_6	78.1	0.0100	0.0137
Cyclohexane	C_6H_{12}	84.2	0.0000	0.0000
2,3-Dimethylpentane	C_7H_{16}	100.2	0.1020	0.1088
3-Methylhexane	C_7H_{16}	100.2	0.0000	0.0000
3-Ethylpentane	C_7H_{16}	100.2	0.0000	0.0000
2,2,4-Trimethylpentane	C_8H_{18}	114.2	0.0000	0.0000
n-Heptane	C_7H_{16}	100.2	0.0800	0.0853
Methylcyclohexane	C_7H_{14}	98.2	0.0000	0.0000
2,2-Dimethylhexane	C_8H_{18}	114.2	0.0000	0.0000

Table B-13
(Concluded)

Component Number	Chemical Formula	$M_{w,i}$ (g)	Initial	
			Mass Fraction	Mole Fraction
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. However, a large group of these models were written for a specific purpose (e.g. a doctoral dissertation) and have not been "maintained" as programs which can be easily obtained and used by design team members. Another group of models are extremely complex and can only be used on a computer work station or mainframe and consequently are not available to the typical engineer. For the purposes of this manual, and because most project engineers have access to IBM-compatible or Apple-compatible personal computers (PCs), the discussion of models is limited to those which can be used on these machines. Table C-1 summarizes these soil vapor flow, contaminant transport, and extraction models which were compiled primarily from USEPA records, Joss (1993), and IT Corporation (1993). Each of these publications provides detailed summaries of the models presented here as well as summaries of more complex models which can be run on work stations and main frame computers.

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 ($M/L\text{-}T^2$).

Output from pressure distribution/airflow models can include:

- Vapor pressure distributions ($M/L\text{-}T^2$).
- Flow rates from constant pressure nodes (L^3/T).
- Vapor velocities (L/T).
- Vapor "particle" pathlines.

a. Models listed in Table C-1 which can be used for these simulations include ABRIOLA, AIRFLOW, AIRTEST, AIR2D, AIR3D, and CSUGAS. 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.

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/ SVE	2-D finite element radial symmetric airflow	Waterloo Hydrologic Software Available to public.	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
AIRTEST, AIR2D, AIR3D	2-D and 3-D analytical radial-symmetric airflow	A.L. Baehr, USGS, C.J. Joss, Drexel University Water Resources Division, Mountain View Office Park 810 Bear Tavern Road Suite 206 West Trenton, NJ 08628	IBM PC/AT compatible, 512K RAM	Permeability test data, initial pressures, flow rates	Permeability, pressure distribution and flow	Easy
CSUGAS	3-D finite difference vapor flow	J. Warner, Colorado State University, Civil Engineering Department, (303)481-8381 Available to public.	IBM PC/AT compatible, DOS 5.1 or higher, 640 KB RAM, graphics monitor, math coprocessor, at least 595K available low memory	Permeability, porosity, initial pressures, topography	Soil pressure distribution; total systems flow	Moderate
Hyper-Ventilate	Screening	Developed by: USEPA and Shell Oil Company Chi-Yaun Fan (Project Officer) 609/292-3131 Available through NTIS: 703/487-4650	Apple Macintosh, 2 Mb RAM "Hypercard" 2.0 or newer -or- IBM 386 or IBM compatible PC, 4Mb RAM, VGA through the use of Spinnaker PLUS in Microsoft Windows version 3.0 or higher	Pemeability, 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. Can simulate the 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
MOD-FLOW	3-D finite difference groundwater flow (converted for air flow calculations)	USGS Available to public.	IBM PC/AT compatible, DOS 3.3 or higher, math coprocessor, graphics monitor	Vapor conductivity, initial pressures	Soil pressure distribution; total system flow	Difficult
MOTRANS	2-D or 3-D finite element, multicomponent transport of water, NAPL and vapor.	Environmental Systems and Technologies, Inc. P.O. Box 10457 Blacksburg, VA 24062-0457 (703)552-0685 Available to public.	IBM PC 386/486 with 8 Mb RAM, math coprocessor, and EGA or VGA graphics card and display. SURFER/GRAPHER is required to view or print.	NAPL viscosity, porosity, hydraulic conductivity, air-water capillary pressure, water/NAPL surface tension ratio, NAPL characteristics	System pressures, saturations, velocities, concentrations in each phase, total phase volume and total component mass	Difficult
STM VOC	1-D, 2-D, and 3-D finite difference, multiphase flow and transport in a 3-fluid-phase porous medium under monisothermal conditions	K. Pruess, Earth Sciences Division, Lawrence Berkeley Laboratory, 1 Cyototron Road, Berkeley, CA 94720 (510)486-6732	Unknown requirements. Code documentation and a user's guide in preparation	Geometry of domain, porosity, permeability, soil grain heat capacity, dry mud saturated media thermal conductivity, steam injection rate, enthalpy of steam	System temperature, pressure and saturation as a function of time and space, cumulative NAPL volume removed.	Difficult
SVE COLUMN	Lab column	D.J. Wilson Available through NTIS: 703/487-4650.	IBM PC/AT compatible, 640 KB RAM; MS-DOS 3.3 or higher. BASIC A	Flow rate, column dimension, porosity, temperature, time step, sorption isotherms	Mass remaining vs. time	Easy
VENTING	Screening	M.W. Kemblowski, Environmental Systems and Technologies, Inc., P.O. Box 10457 Blacksburg, Virginia 24062-0457 (703)552-0685 Available to public.	IBM/PC with 640K RAM, math coprocessor, and CGA, EGA or VGA graphics card and display.	Airflow/permeability, containment characteristics	Mass removal rate curve for each spill component, tabular output	Easy
MPNEG	1-D steady state advective-dispersive, finite difference, vapor flow and transport	M.L. Brusseau, Water Resources Research, 1991. 27(12): 3189-3199.	IBM PC 386 or compatible, 2 Mb RAM, math coprocessor, and hard disk	Permeability, gas characteristics, chemical characteristics	Soil pressures, chemical concentrations	Easy
ABRIOLA	2-D transient, finite difference, vapor flow	L. Abriola, and K. Rathfelder (313)764-6487	IBM PC Compatible 386/486	Permeability, initial pressures, temperature	Soil pressure distributions	Easy with limitations

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.

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.

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

$$k_i = \frac{K\mu}{\rho g} \tag{D-1}$$

where

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

K = saturated hydraulic conductivity, $[L/T]$

μ = dynamic viscosity of water, $[M/L\text{-}T]$

ρ = density of water, $[M/L^3]$

g = gravitational constant, $[L/T^2]$

a. The relationship between air permeability and intrinsic permeability is typically expressed as

$$k = k_i * k_{ra} \tag{D-2}$$

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

$$k_{ra} = (1 - S_e)^2 \left(1 - S_e^{\frac{2+\lambda}{\lambda}} \right) \tag{D-3}$$

where

S_e = effective water saturation

λ = Brooks-Corey pore size distribution index

c. Effective water saturation S_e is further defined as

$$S_e = \frac{S_w - S_r}{1 - S_r} \tag{D-4}$$

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

$$k = (1 - S_e)^2 \left(1 - S_e^{\frac{2+\lambda}{\lambda}} \right) \frac{K\mu}{\rho g} \tag{D-5}$$

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)

$$k_i = 0.125r^2 \qquad \text{(D-6)}$$

where

k_i = intrinsic permeability, darcies

r = characteristic pore radius (mm), defined as

$$r = cD_{15} \qquad \text{(D-7)}$$

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

$$k = 1{,}250D_{15}^2 \qquad \text{(D-8)}$$

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 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 1-½ 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

$$k_a = -\frac{RT\mu Q_m}{2\pi b M P_{atm}^2 slope} \qquad \text{(D-9)}$$

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 2-4*d*).

(5) As described in paragraph 2-4*c*, the solution to the linearized PDE for a constant sink at $r = 0$, with $P = P_{atm}$ at $r = \infty$, is (Johnson et al. 1990b):

$$P - P_{atm} = \frac{Q_v \mu}{4\pi b k_a} \int_u^\infty \frac{e^{-x}}{x} dx \qquad \text{(D-10)}$$

where

P = absolute pressure [M/LT^2]

P_{atm} = atmospheric pressure [M/LT^2]

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

μ = dynamic viscosity [M/LT^2]

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

x = a dummy variable of integration, and

$$u = \frac{r^2 n_a \mu}{4 k_a P_{atm} t} \tag{D-11}$$

where

r = radial distance [L]

n_a = air-filled porosity [L^3/L^3]

t = time

(6) Equation D-10 is sometimes written as

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} W\ (u) \tag{D-12}$$

where $W(u)$ is the Theis well function. Equation D-12 can be solved for air permeability as:

$$k_a = \frac{Q_v \mu W(u)}{4 \pi b k_a (P - P_{atm})} \tag{D-13}$$

and Equation D-11 can be solved for air-filled porosity as:

(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 subsituted into Equations D-13 and D-14 to obtain values of air permeability and air-filled porosity.

$$n_a = \frac{4 k_a P_{atm} t}{r^2 \mu} u \tag{D-14}$$

(8) In a similar manner, plots of P - P_{atm} versus time can be fitted to type curves for the leaky well function (paragraph 2-4*c*) 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 2-4*c*). The Cooper-Jacob approximation applies when $u \leq 0.01$ (i.e., small radial distances or large values of time), and is written as:

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} \left(\ln \frac{4 k_a P_{atm} t}{r^2 n_a \mu} - 0.5772 \right) \tag{D-15}$$

(10) When $u \leq 0.01$, a plot of pressure vs $ln(t)$ should show a straight line with slope:

$$m = \frac{Q_v \mu}{4 \pi b k_a} \tag{D-16}$$

where

m = the change in pressure over one log cycle

(11) The time intercept when P - P_{atm} = 0 should occur is:

$$\ln \frac{4 k_a P_{atm} t_o}{r^2 n_a \mu} = 0.5772 \tag{D-17}$$

where

t_o = the time intercept when P - P_{atm} = 0

(12) Equation D-16 can be rearranged in terms of air permeability:

$$k_a = \frac{Q_v \mu}{4 \pi b m} \tag{D-18}$$

(13) Likewise, equation D-17 can be solved for the air-filled porosity:

$$n_a = 2.25 \frac{k_a P_{atm} t_o}{r^2 \mu} \tag{D-19}$$

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 $u \leq 0.01$, 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:

$$t = \frac{r^2 n_a \mu}{4 k_a P_{atm} \varepsilon} \qquad \text{(D-20)}$$

where

ε = 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 vaccums (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 $u \leq 0.01$. This condition is known as the pseudo-steady state (McWhorter and Sunada 1977), and is described in paragraph 2-4*d*.

(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:

$$k_a = \frac{Q_v P^* \mu}{\pi b} \frac{\ln(r_2/r_1)}{P_1^2 - P_2^2} \qquad \text{(D-21)}$$

where

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

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 (paragraph 2-4*c*).

(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 2-28, 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.

$$\begin{aligned} P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L - l)} \Bigg\{ & \ln\left[\frac{z - l + \sqrt{r^2 + (z-l)^2}}{z - L + \sqrt{r^2 + (z-L)^2}} \cdot \frac{z + L + \sqrt{r^2 + (z+L)^2}}{z + l + \sqrt{r^2 + (z+l)^2}}\right] \\ & - \sum_{n=1}^{\infty} (-1)^n \ln\left[\frac{z - 2nb + L + \sqrt{r^2 + (z-2nb+L)^2}}{z - 2nb + l + \sqrt{r^2 + (z-2nb+l)^2}} \cdot \frac{z - 2nb - L + \sqrt{r^2 + (z-2nb-L)^2}}{z - 2nb - l + \sqrt{r^2 + (z-2nb-l)^2}}\right. \\ & \left. \cdot \frac{z + 2nb - L + \sqrt{r^2 + (z+2nb-L)^2}}{z + 2nb - l + \sqrt{r^2 + (z+2nb-l)^2}} \cdot \frac{z + 2nb + L + \sqrt{r^2 + (z+2nb+L)^2}}{z + 2nb + l + \sqrt{r^2 + (z+2nb+l)^2}}\right] \Bigg\} \end{aligned} \qquad \text{(D-22)}$$

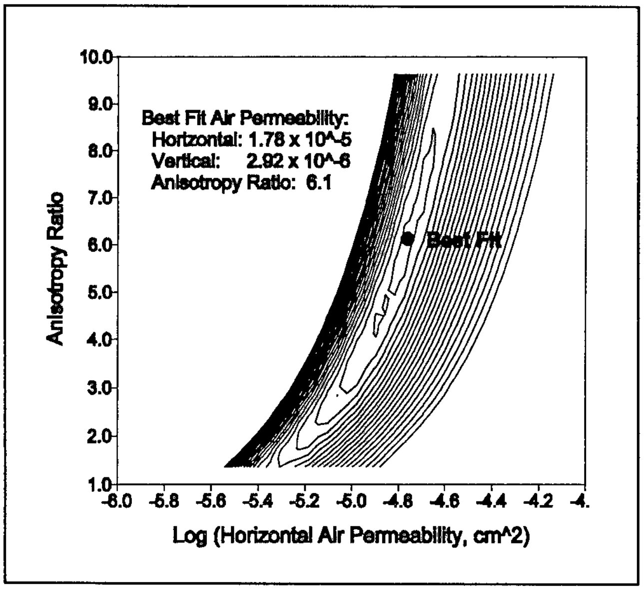

Figure D-1. Best fit of field data using Equation D-22

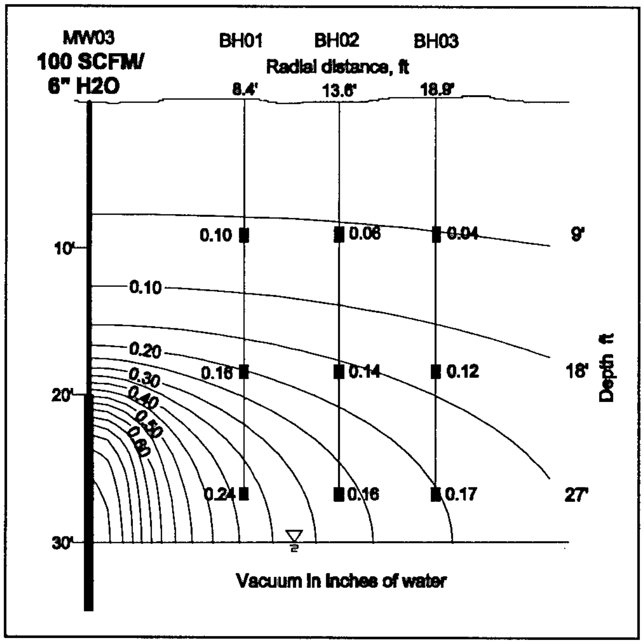

Figure D-2. Pressure isobars calculated using Equation D-22 and best-fit air permeabilities from Figure D-1

d. 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).

Appendix E
Index

Numerals before and after colons designate chapters and pages respectively (e.g., 3:5 designates page 3-5).

Italicized numerals refer to figures illustrating the subject mentioned.