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

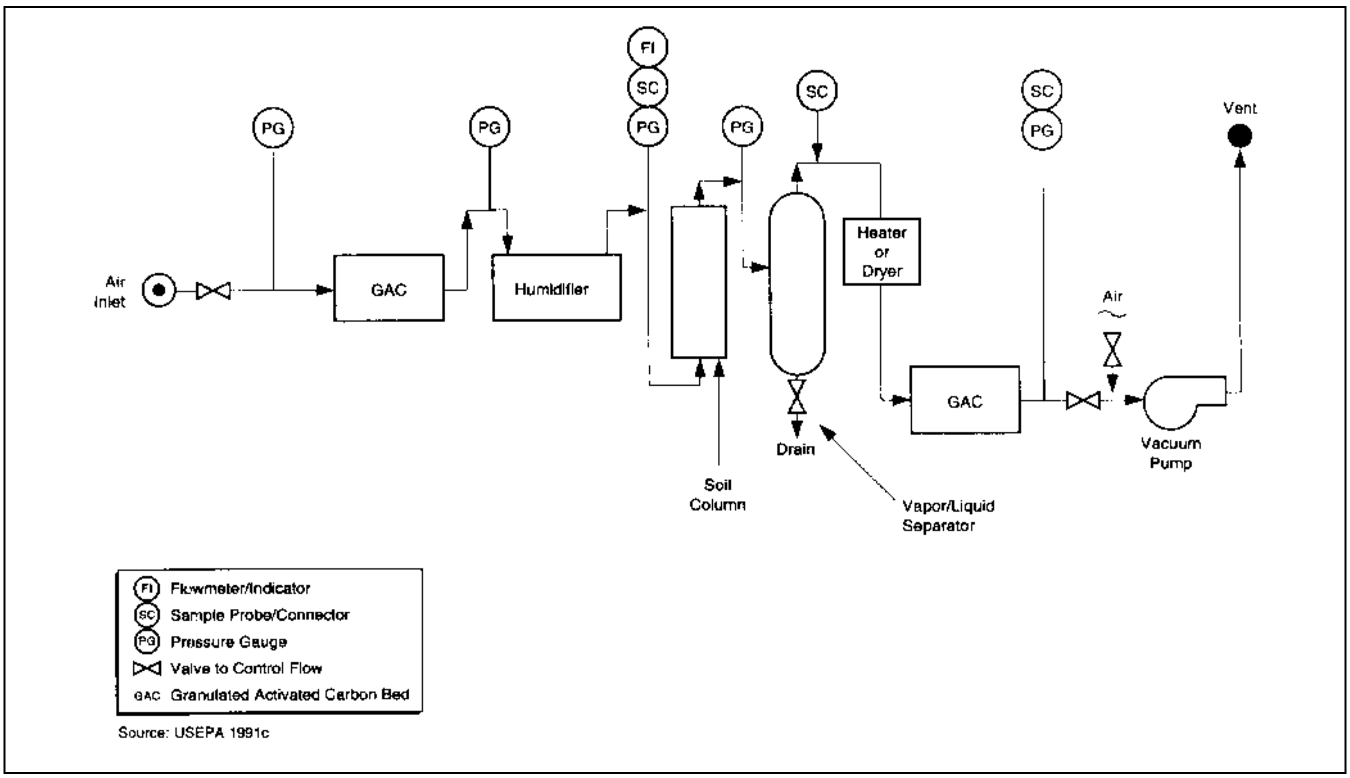

Figure 4-1. Diagram of typical column test apparatus

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

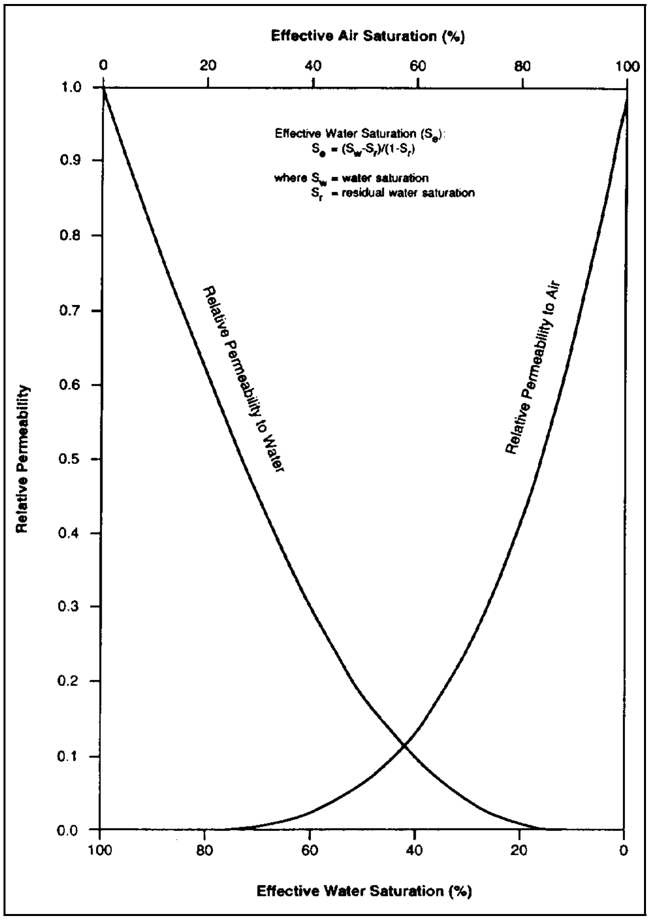

Figure 4-2. Relationship between water saturation and relative permeability to air

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.

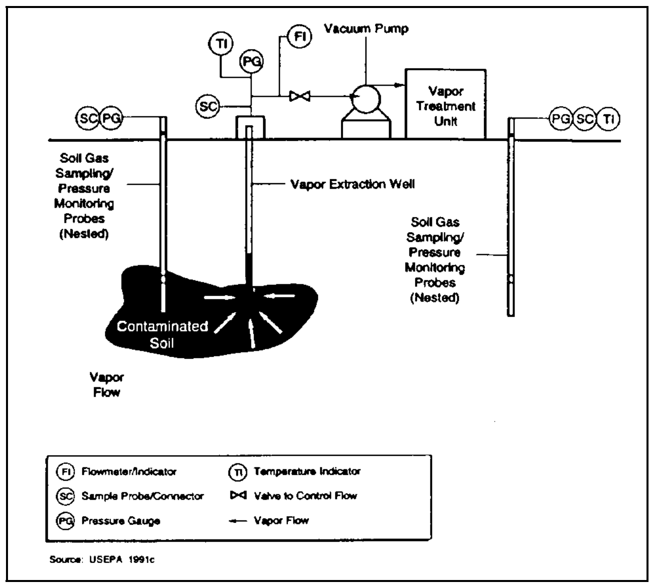

Figure 4-3. Schematic for typical air permeability or pilot test

(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 step-wise, 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).

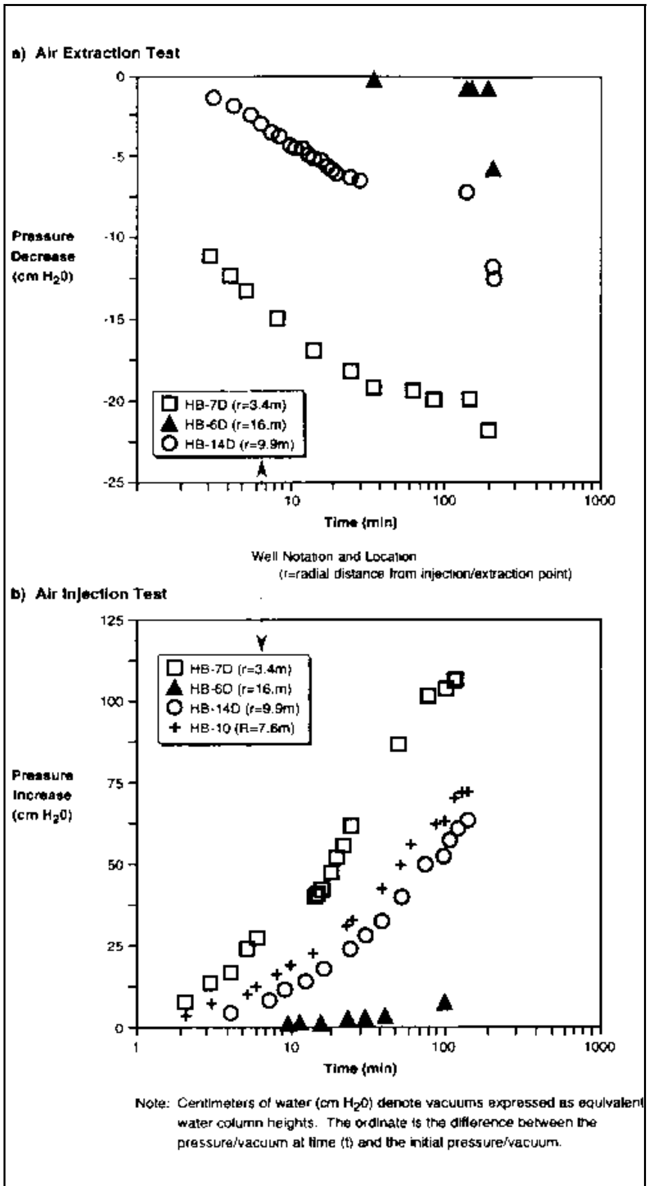

Figure 4-4. Typical field air permeability test data

(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™ 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™ 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

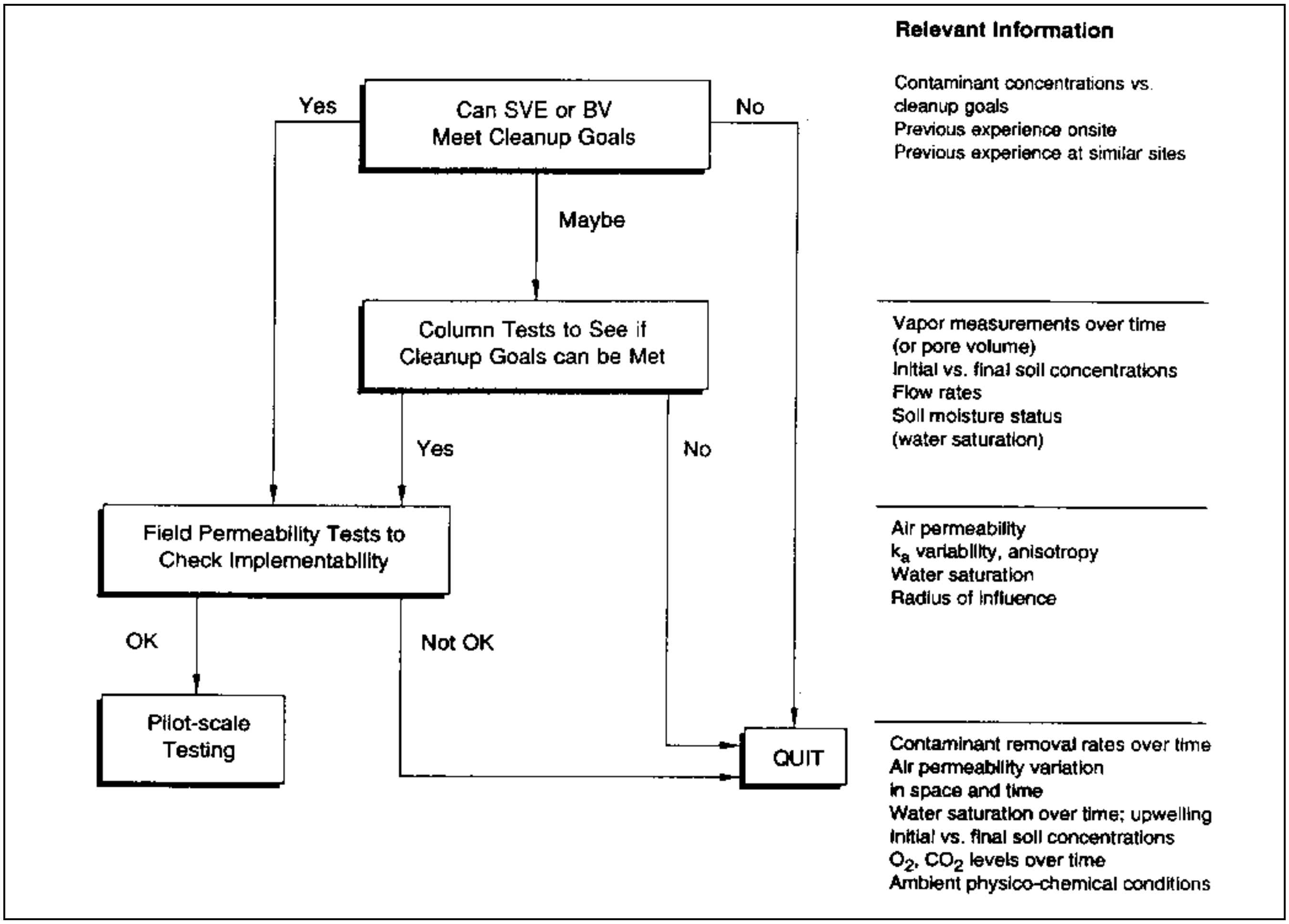

Figure 4-5. Bench- and pilot-scale testing decision tree

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.

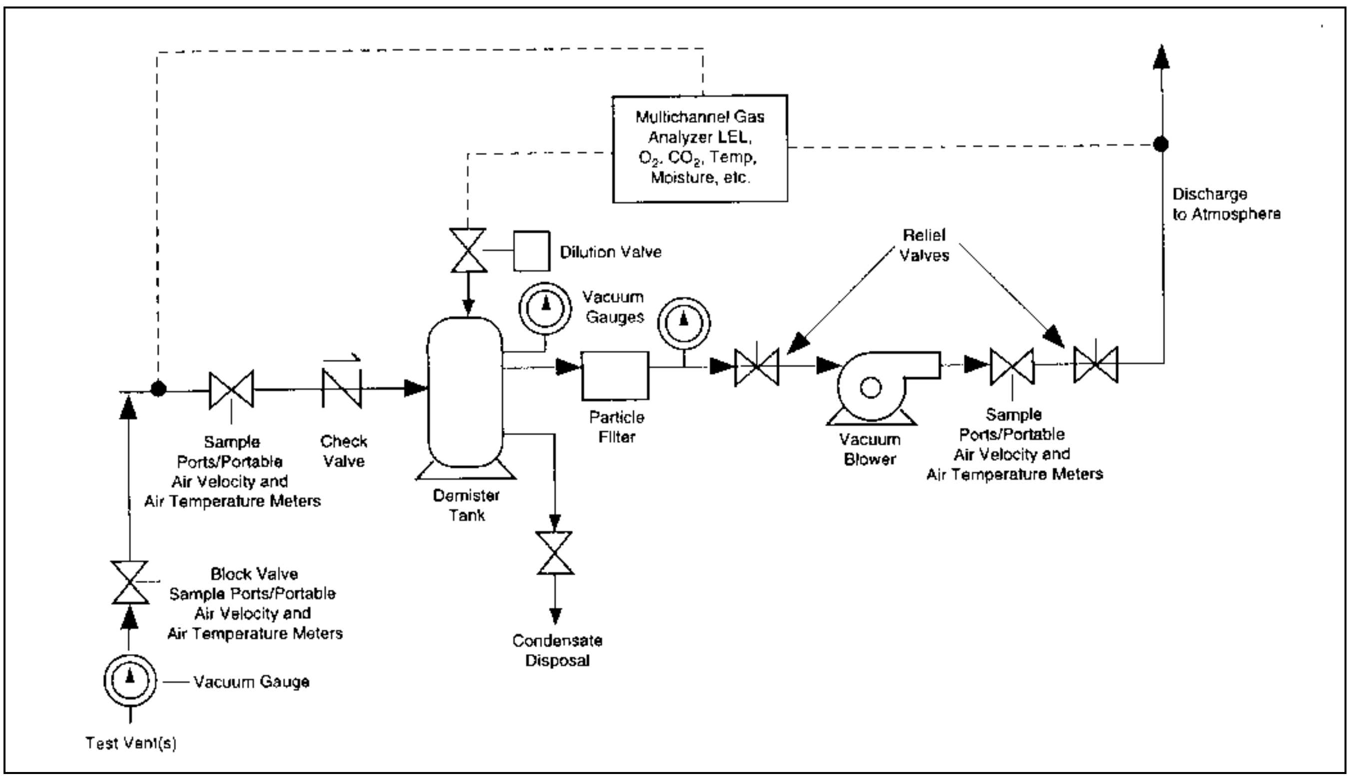

Figure 4-6. SVE/BV system performance test typical process

- 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.

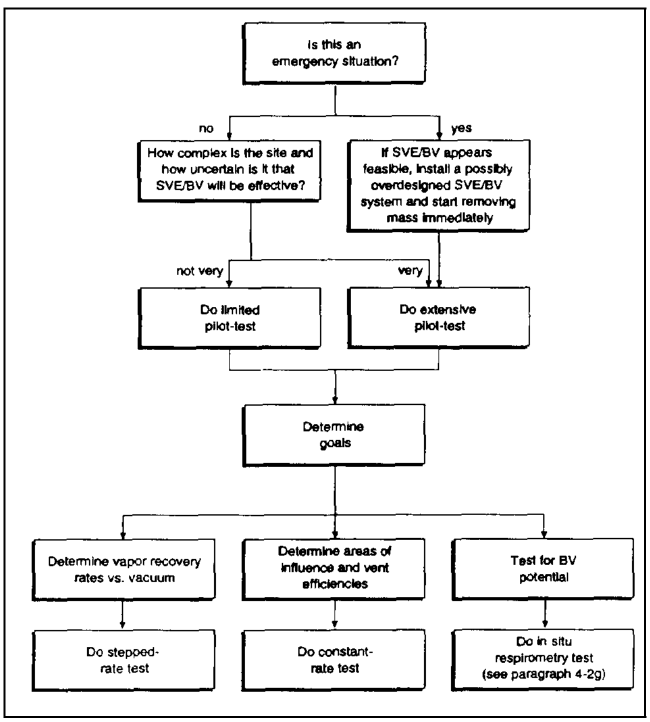

Figure 4-7. Pilot-testing decision tree

(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).

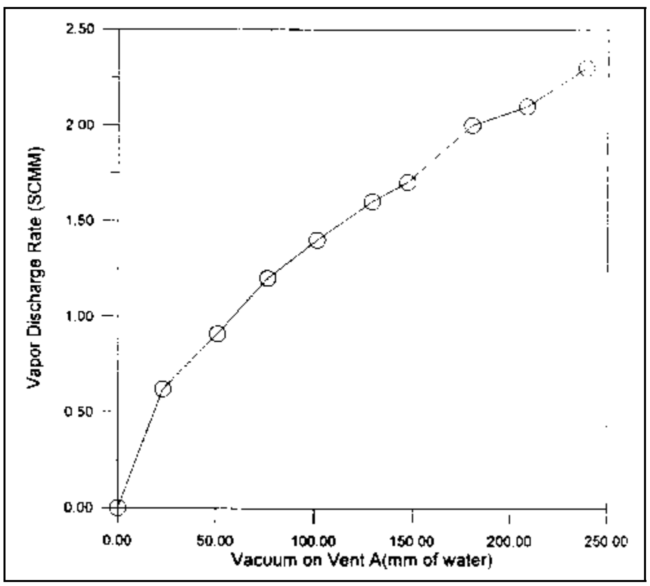

Figure 4-8. Stepped-rate test example for a horizontal vent

(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:

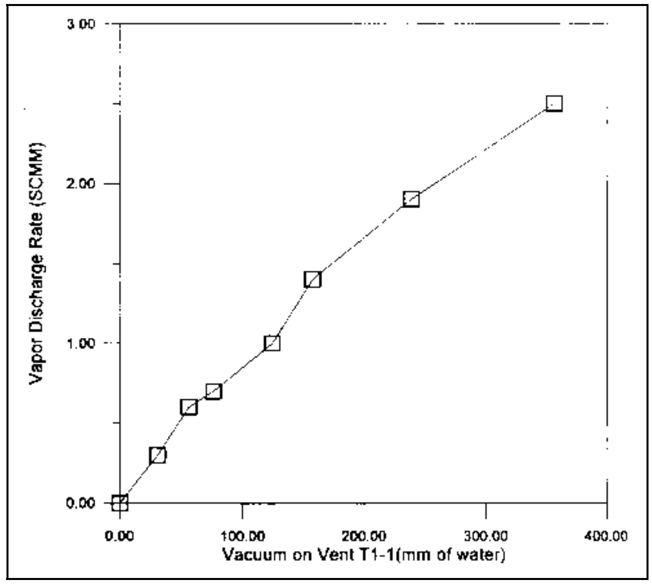

Figure 4-9. Stepped-rate test example for a vertical vent

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

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:

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

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

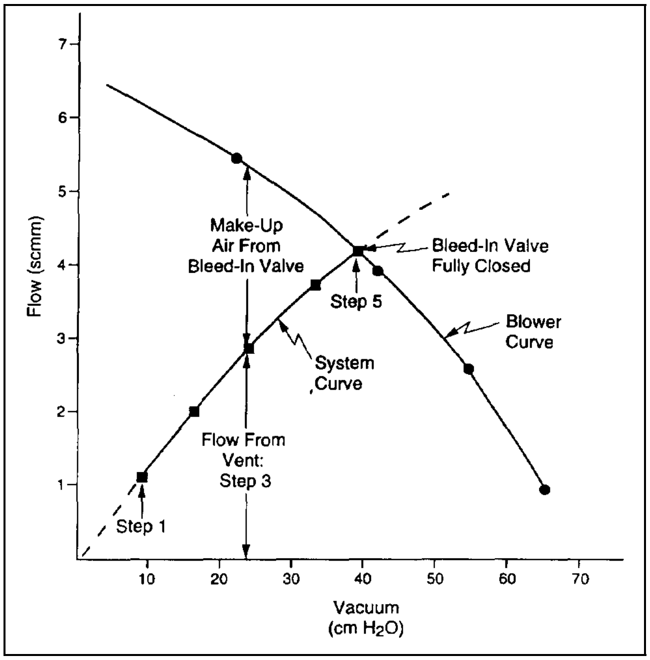

Figure 4-10. Example of system curve construction from stepped rate test

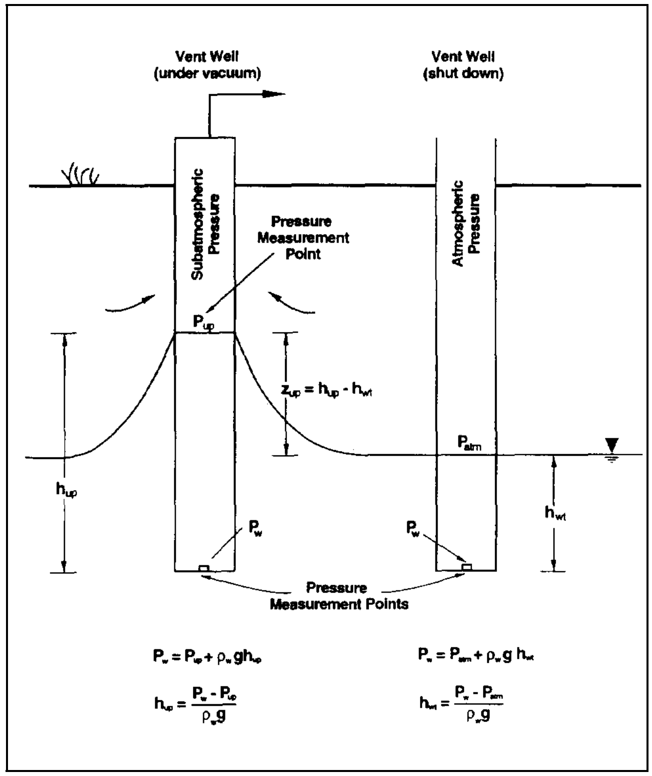

Figure 4-11. Monitoring upwelling

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

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

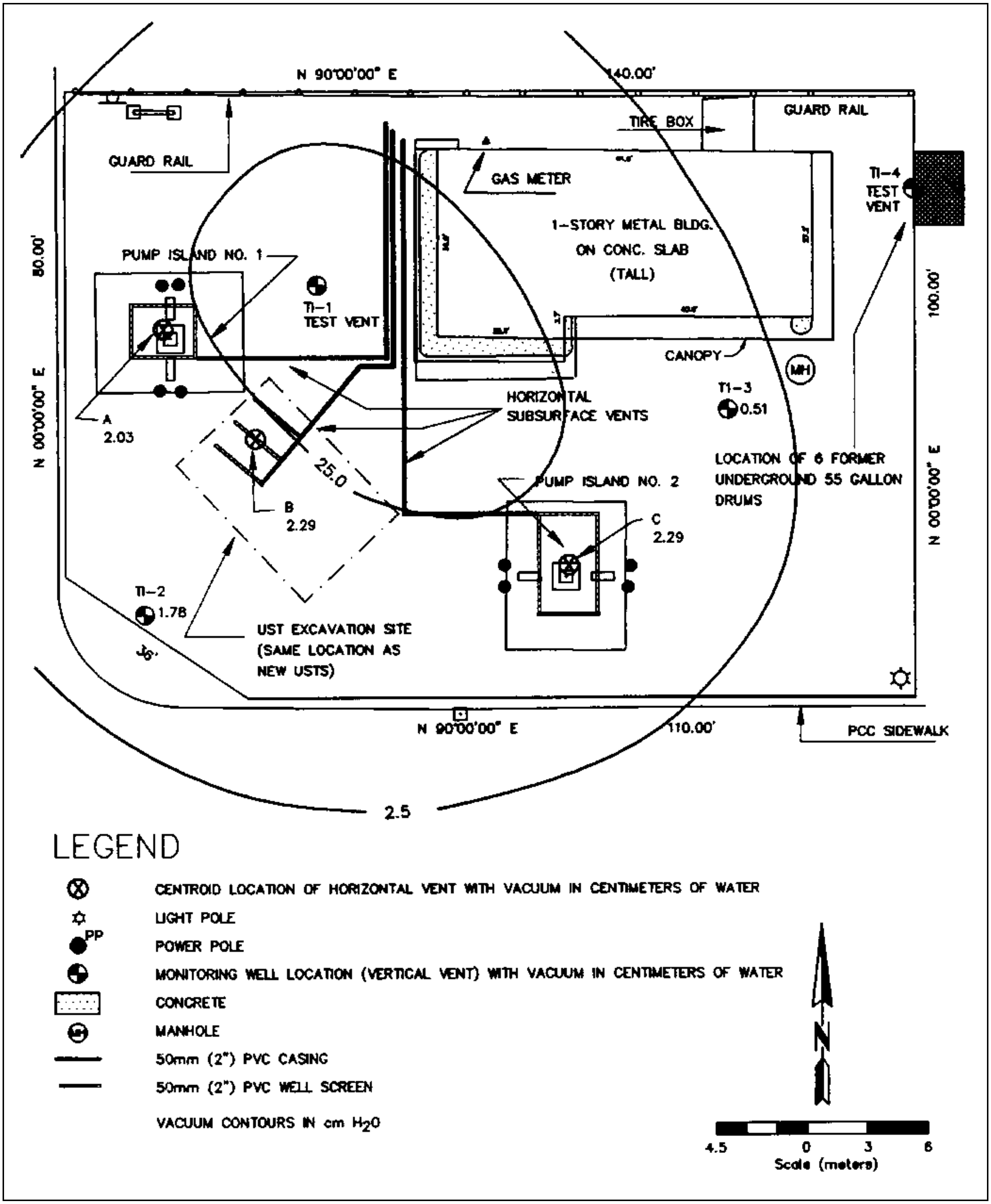

Figure 4-12. Example vacuum map for constant-rate test, vertical vent

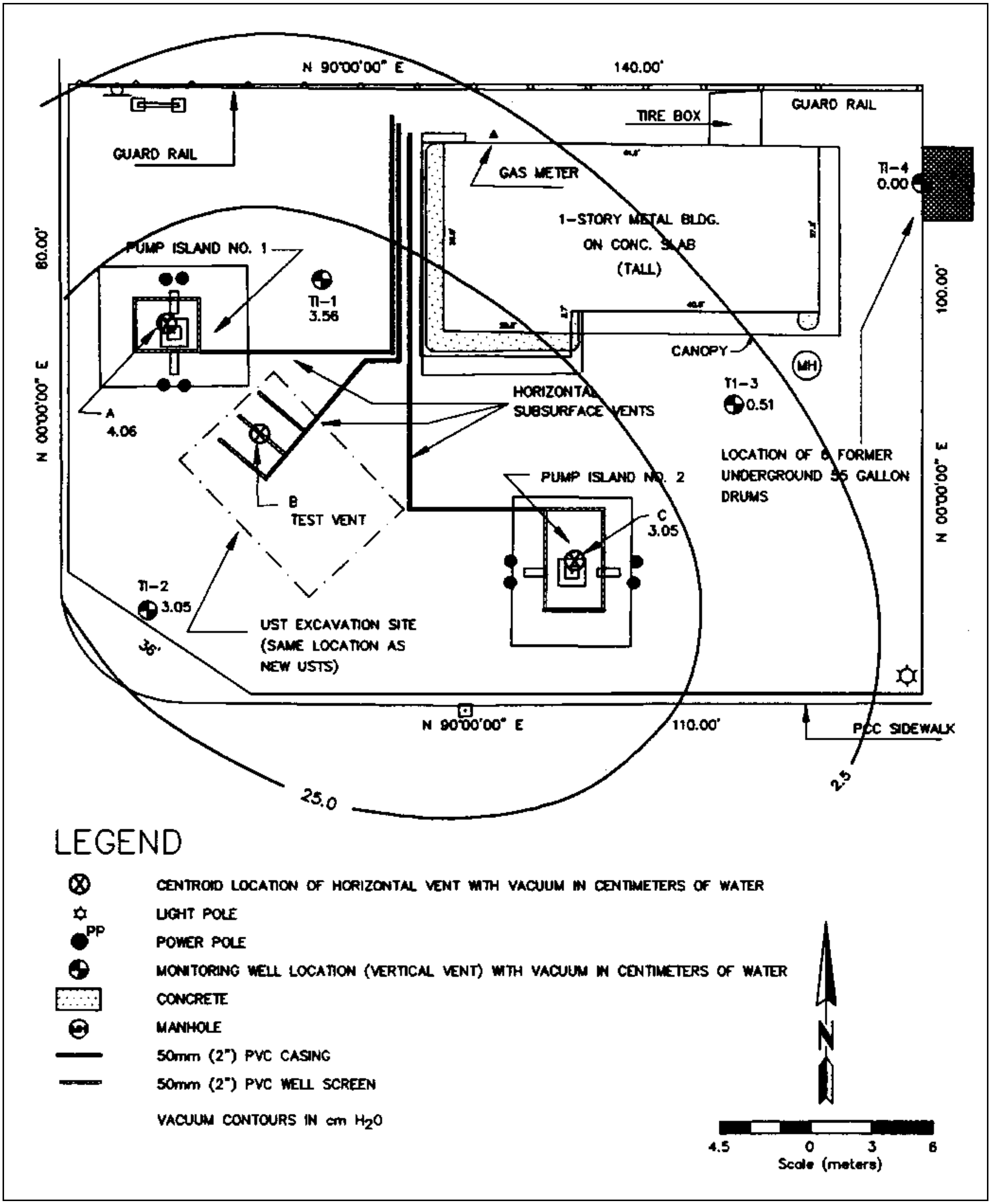

Figure 4-13. Example vacuum map for constant-rate test, horizontal vent

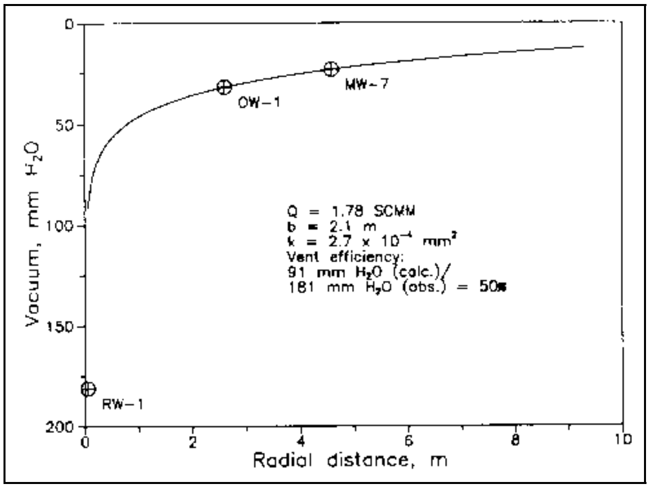

Figure 4-14. Steady-state pump test

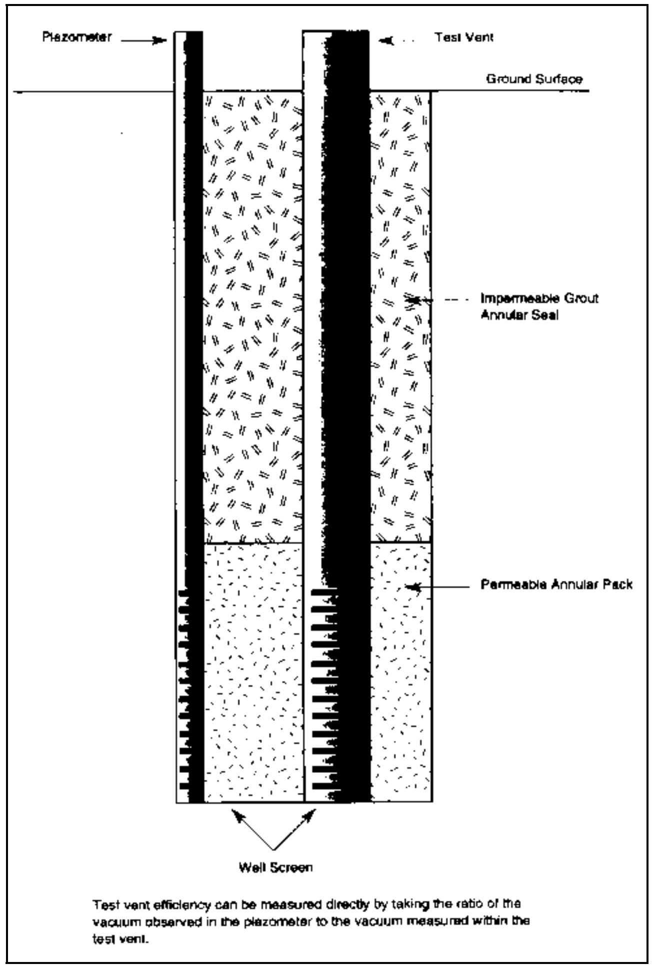

Figure 4-15. Test vent

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.

(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)

$r_1 \quad < r_2$

(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 (~1.01 × 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

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

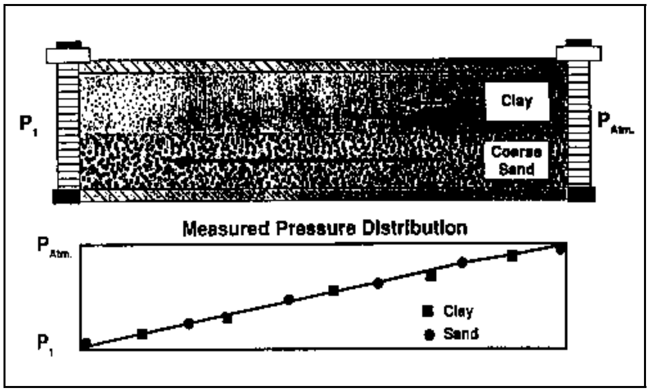

Figure 4-16. Steady-state pressure distribution for 1-D flow between parallel trenches installed in confined layers. Lengths of horizontal arrows indicate relative air velocity. Note that measurable pressure/vacuum readings are no guarantee of significant vapor flow (after Johnson and Ettinger 1994)

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

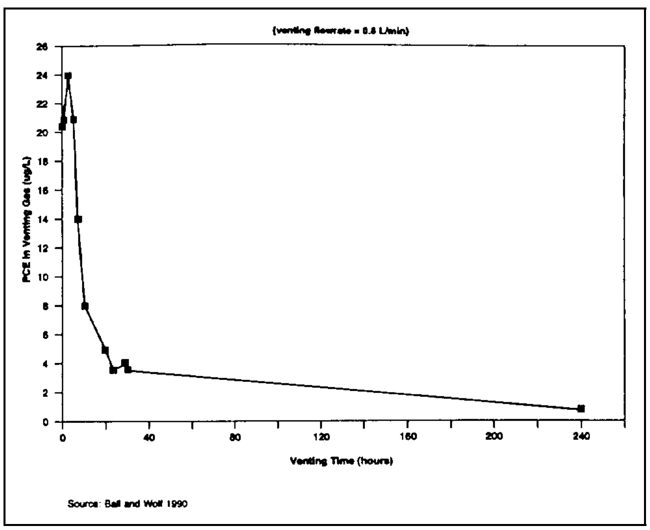

Figure 4-17. Tetrachloroethene (PCE) venting curve

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

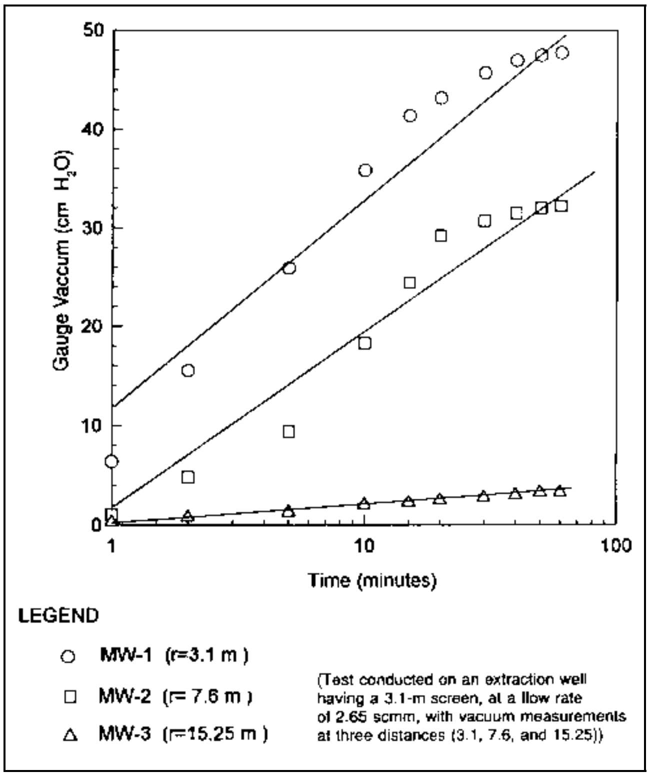

Figure 4-18. Semi-log plot of vacuum versus time for air permeability test

(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

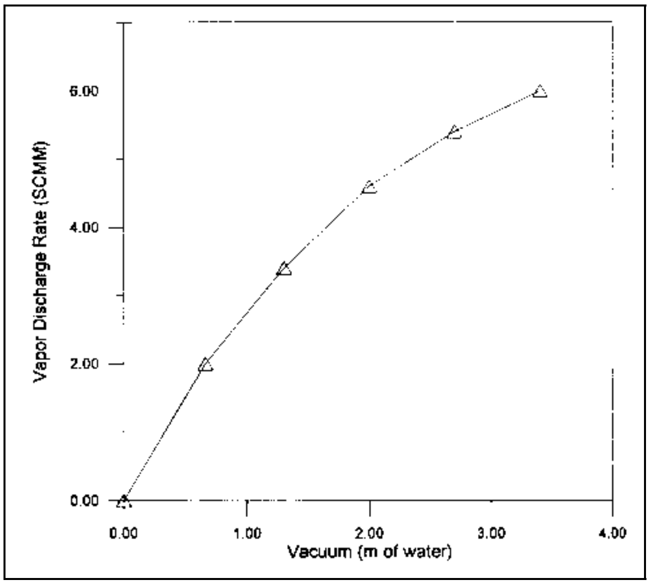

Figure 4-19. Extraction rate versus vacuum

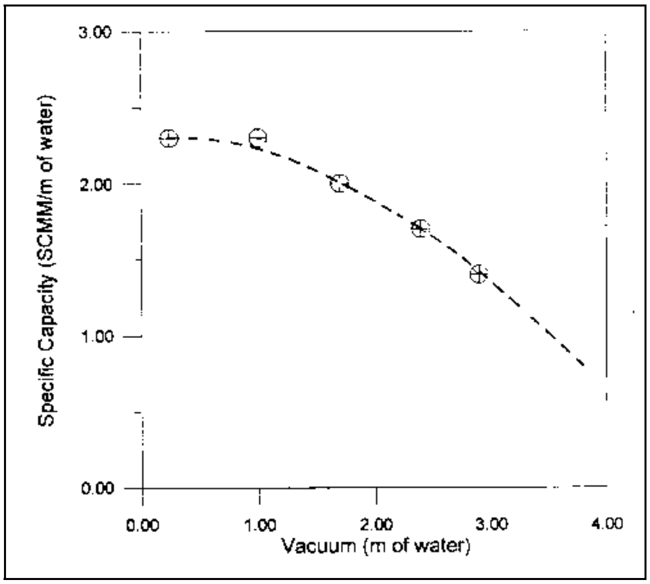

Figure 4-20. Specific capacity versus vacuum

(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.

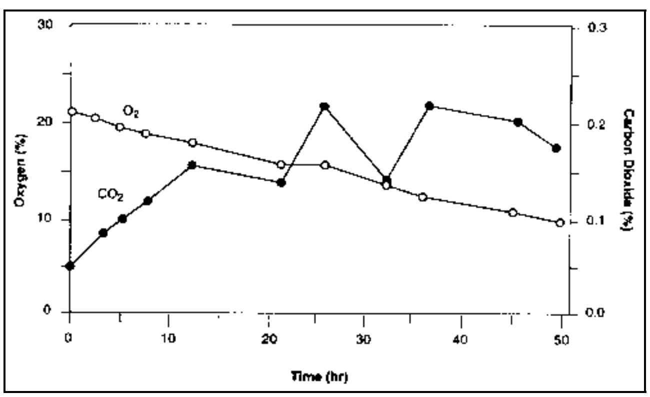

Figure 4-21. O_2 and CO_2 percentages versus time during in situ respirometry test

(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:

$$C_6H_{14} + 9.50_2 \rightarrow 6C0_2 + 7H_20 \qquad (4\text{-}12)$$

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

$$K_B = -K_o A D_o C/100 \qquad (4\text{-}13)$$

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:

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

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.

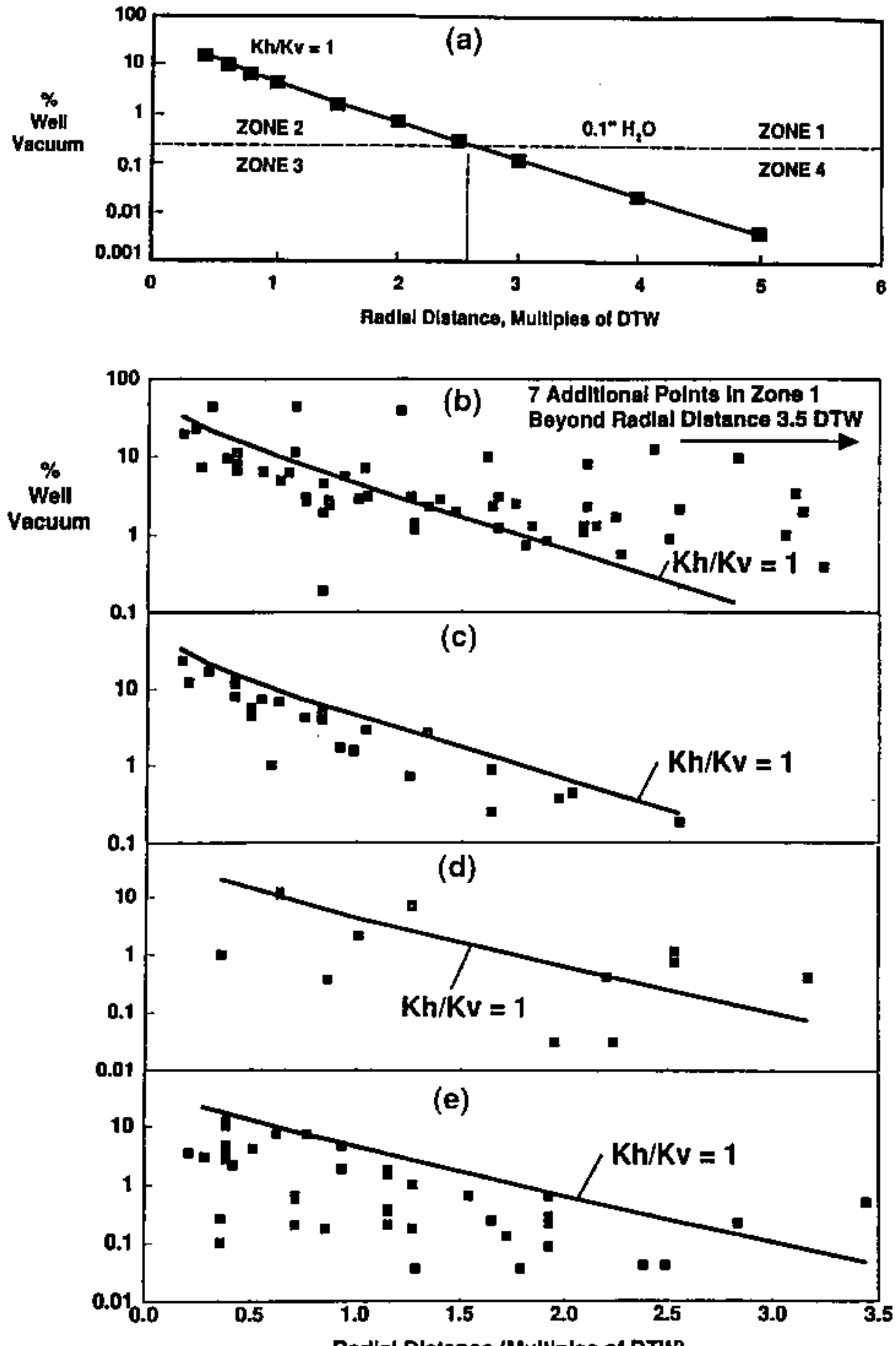

Figure 4-22. Field criteria for estimating venting feasibility, and evaluation of data from 22 pilot tests. (a) Vacuum distribution zones for pass/fail criteria; (b) High K sites passing field criteria; (c) High K sites failing field criteria; (d) Low K sites passing field criteria; (e) Low K sites failing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