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ENHANCED ATTENUATION TECHNOLOGIES

Passive Soil Vapor Extraction

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Revision 1 of this document was issued to correct the following error:

In the original printing the graphics in Figures 3.1a and 3.1b were inverted and thus were not reflective of the associated captions.

FOREWORD

Enhanced Attenuation (EA) is a strategy where engineered remediation activities support and extend natural attenuation processes and assures the sustainability of those attenuation mechanisms. The Interstate Technology and Regulatory Council (ITRC), a national regulator led organization with the goal of encouraging adoption of useful-innovative environmental technologies, defined and described EA in a technical regulatory document published in 2008 (ITRC, 2008). EA supports the transition from source and active treatments to monitored natural attenuation and supports the concepts of treatment trains and combined remedies.

There are two general classes of EA applications: 1) those that reduce the release of contaminant from a source into the groundwater plume; and 2) those that increase the natural attenuation capacity in the subsurface. For the most part, the technologies to accomplish these objectives are already in use as traditional active treatments. In an EA approach, technologies are deployed to create an environment that will foster a transition to MNA once the active treatment is complete and will sustain and enhance important natural attenuation mechanisms until remediation goals are met.

To illustrate EA and encourage broader use of the strategy, several user guides that describe the selection, design and performance of key technologies are now being developed by the Savannah River National Lab in collaboration with partners. These guides provide information to support the implementation of EA as described in the ITRC technical regulatory document (ITRC, 2008) and serve as supplementary resources to environmental professionals, regulators and managers in developing technically sound plans to clean up contaminated sites.

Passive Soil Vapor Extraction

EXECUTIVE SUMMARY

Passive soil vapor extraction (PSVE) is an enhanced attenuation (EA) approach that removes volatile contaminants from soil. The extraction is driven by natural pressure gradients between the subsurface and atmosphere (Barometric Pumping), or by renewable sources of energy such as wind or solar power (Assisted PSVE). The technology is applicable for remediating sites with low levels of contamination and for transitioning sites from active source technologies such as active soil vapor extraction (ASVE) to natural attenuation. PSVE systems are simple to design and operate and are more cost effective than active systems in many scenarios. Thus, PSVE is often appropriate as an interim-remedial or polishing strategy. Over the past decade, PSVE has been demonstrated in the U.S. and in Europe. These demonstrations provide practical information to assist in selecting, designing and implementing the technology. These demonstrations indicate that the technology can be effective in achieving remedial objectives in a timely fashion. The keys to success include:

1) *Application at sites where the residual source quantities, and associated fluxes to groundwater, are relatively low;*

2) *Selection of the appropriate passive energy source – barometric pumping in cases with a deep vadose zone and barrier (e.g., clay) layers that separate the subsurface from the atmosphere and renewable energy assisted PSVE in other settings and where higher flow rates are required.*

3) *Provision of sufficient access to the contaminated vadose zones through the spacing and number of extraction wells.*

This PSVE technology report provides a summary of the relevant technical background, real-world case study performance, key design and cost considerations, and a scenario-based cost evaluation. The key design and cost considerations are organized into a flowchart that dovetails with the Enhanced Attenuation: Chlorinated Organics Guidance of the Interstate Technology and Regulatory Council (ITRC). The PSVE flowchart provides a structured process to determine if the technology is, or is not, reasonable and defensible for a particular site. The central basis for that decision is the expected performance of PSVE under the site specific conditions. Will PSVE have sufficient mass removal rates to reduce the release, or flux, of contamination into the underlying groundwater so that the site can meet it overall remedial objectives?

The summary technical information, case study experiences, and structured decision process provided in this “user guide” should assist environmental decision-makers, regulators, and engineers in selecting and successfully implementing PSVE at appropriate sites.

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1.0 TECHNOLOGY SUMMARY

1.1 Problem Statement

More than a decade after the deployment of active source remediation technologies at chlorinated solvent sites, many still do not meet MNA or site closure requirements. In a survey of 59 chlorinated solvent sites (McGuire et al., 2005) where active source treatment technologies - chemical oxidation, enhanced bioremediation, thermal treatment, and surfactant/co-solvent flushing – were implemented, none of the technologies were able to achieve maximum contaminant levels (MCLs) 1 to 5 years after the treatment. Furthermore, despite the fact that active technologies no longer offer the cost-benefits required to continue operation at many of these sites, discontinuing source treatment is not considered an acceptable option due to the potential for the residual mass to act as a long-term source of low-level groundwater contamination.

For such sites, there is an immediate need for the development of innovative low-cost, low-energy technologies that can accelerate the transition from active technologies to MNA and/or site-specific remedial objectives. Additionally, there is a need for establishment of a widely-accepted framework for the selection and long-term monitoring of these passive technologies.

1.2 Solution

Passive soil vapor extraction (PSVE) is a broad term that encompasses low-energy soil vapor extraction technologies for remediating unsaturated soils impacted with volatile contaminants. Two general processes are used to extract volatile contaminants from impacted soils within the unsaturated zone:

- *Barometric pumping applications*, which exploit the natural diurnal and weather-driven venting cycles between the atmosphere and the subsurface environment; and
- *MicroBlower applications*, in which small blowers powered by renewable energy sources (e.g., solar or wind) are used.

Ideally, PSVEs can be employed at sites where the mass loading from the source zone are intermittent or low. For example, low permeability soils with diffusion-limited gas transport and/or residual concentrations of volatile contaminants are the most likely candidates for a PSVE application. By virtue of their technological simplicity and low cost, PSVEs are ideal as an interim strategy or as a polishing strategy at sites where the mass flux reduction achieved by an active SVE technology no longer justifies the cost of the operation. Since well design for a PSVE application is identical to that for an ASVE application, transitioning from an ASVE remediation program to a PSVE program could be inexpensive and rapid.

1.3 How It Works

Barometric Applications: Disequilibrium between the atmospheric pressure and the subsurface pressure results in a flow of air from the zone of high pressure to the zone of low pressure when the two zones are directly connected as by a well. As a result of this pressure difference, under natural circumstances, wells screened within the unsaturated zone have been shown to "breathe", i.e., inhale ambient air from the atmosphere during high atmospheric pressure conditions and exhale soil gas to the atmosphere during low atmospheric pressure conditions. Barometric applications aim to exploit the "exhalation" behavior in wells screened within the impacted soil layers in the unsaturated zone by installing a passive one-way check valve that allows flow of soil gas into the atmosphere when the pressure in the well is greater than the atmospheric pressure and seals the well when the atmospheric pressure is greater than the pressure in the well. By preventing dilution of soil gas with ambient air, the one-way passive control valve has been shown to increase mass removal of VOCs by barometric pumping by at least a factor of 2 (Rohay et al. 1997; Rossabi, 1999). A network of such wells screened within contaminated layers of the vadose zone could effectively remove residual contaminant mass during the course of a long-term remediation project.

In the last 10 years, researchers have explored a variety of check valves for use in barometric applications:

1. Mylar Flapper Valve patented by Science and Engineering Associates and used in conjunction with Barometrically Enhanced Remediation Technology (BERT™) (ITSER, 2000);

2. Mylar Disk patented by Idaho National Engineering and Environmental Laboratory (INEEL); and

3. Baroball™ Control Valve is a trademark of Westinghouse Savannah River Company, LLC.

Figure 1.1: Devices used for Barometric Applications: (a) BERT™ Flapper Valve; (b) Baroball™ Control Valve

All three check valves are sensitive to pressure differences between the atmosphere and the subsurface and allow outflow of soil gas at pressure gradients less than approximately 1 mbar (cracking pressure). During negative pressure differential conditions, the valve (either the mylar flap, disk or ball) is designed to maintain a seal to prevent inflow of ambient air into the subsurface environment. Riha (2001) reported soil vapor flow rates ranging between 15 and 50 cubic feet per minute (cfm) in 2-inch extraction wells located at the M-Area Process Sewer Line (MAPSL) site at the Savannah River Site (SRS), South Carolina.

MicroBlower Applications: Small blowers can be used to exert a constant and consistent vacuum level on the extraction wells. While similar in design to an ASVE blower, PSVE blowers are low-cost alternatives that are designed to run on renewable sources of energy such as solar and wind energy. By using renewable sources of energy (such as solar panels), the blowers eliminate the need for an external power supply and other ancillary infrastructure generally required for conventional ASVE systems. For most applications, a small battery bank can be used to store power for when the sun or wind energy is inadequate.

1.4 Deployment Summary

Over the past decade, passive soil vapor extraction has been tested successfully at a number of demonstrations around the US (See Table 1). At a majority of these sites, all or a portion of the existing ASVE wells were converted to PSVE by installing a one-way valve or a MicroBlower. Several of these demonstrations were conducted at the Savannah River Site (SRS), SC. For barometric applications, these SRS demonstrations involved 8 to 25 PSVE wells where airflow rates of 1 to 7 scfm were achieved, resulting in the removal of 100 lb to over 700 lb of contaminant mass per site over the individual operating periods. Similarly, MicroBlowers have been installed at two wells at one of these SRS sites to specifically target an area of high concentration (60 ppmv tetrachloroethylene (PCE) and 40 ppmv trichloroethene (TCE)). This assisted PSVE application is capable of achieving consistently high (> 10 scfm) average operating airflow rates and has successively reduced vapor concentrations by approximately an order of magnitude over a 5-year operating period. See Section 4 for results of demonstrations conducted at individual sites.

Table 1.1: Summary of Pilot and Full-Scale Studies Conducted in the United States.

No.	Demonstration Site	Reference
BERT^{TM} Applications		
•	Idaho National Engineering and Environmental Laboratory (INEEL) Radioactive Waste Management Complex, ID	ITSER, 2000
•	Los Alamos National Laboratory, NM	ITSER, 2000
BaroBall^{TM} Applications		
•	Miscellaneous Chemical Basin (MCB), Savannah River Site (SRS), SC	Riha et al., 2005a
•	Metals Laboratory (MetLab), SRS, SC	Riha, 2005b
•	M-Area Process Sewer Line (MAPSL), SRS, SC	Riha et al., 2001
•	Hanford Site, WA	Rohay et al., 1993
•	Four Sites in Denmark	Christensen et al., 2003
MicroBlower Applications		
•	Marine Corps Air Ground Combat Center in Twenty-Nine Palms, CA (Wind-powered)	O'Brian, 2001
•	M-Area Abandoned Process Sewer Line (MAPSL), SC (Solar-powered)	Riha, 2005c

Note: Detailed information about the site application of the INEEL mylar disk were not available in literature and were therefore not included in the table.

1.5 Commercial Availability and Contacts

- *BERT^{TM} Mylar Flapper Valve*: The valves are not available commercially. For technical information or a copy of the patent, contact
  - William (Bill) E. Lowry, Mission Solutions Group, QinetiQ North America. e-mail: Bill.Lowry@QinetiQ-NA.com
  - Eric Miller, Organic Contaminants in the Vadose Zone, WAG–7 Lockheed Martin, Idaho Technologies Company, e-mail: ecm@inel.gov, Telephone: (208) 526-9410
- *INEEL Mylar Disk* : The valves are not available commercially. For technical information or a copy of the patent, contact the Technical Transfer Office at Idaho National Laboratory at www.inl.gov

- *<u>Baroball™ Control Valve and MicroBlower Applications</u>*: The valve is commercially available through Durham Geo Slope Indicator (DGSI), 2175 West Park Court, Stone Mountain, GA 30087. Tel: 800-837-0864; Fax: 770-465-7447. MicroBlowers are not yet available commercially.

  For technical information, contact

  - Brian B. Looney, Environmental Science and Biotechnology Section, Savannah River National Laboratory, SC. Telephone: 803-725-3692, Email: brian02.looney@srnl.doe.gov

  - Brian Riha, Environmental Science and Biotechnology Section, Savannah River National Laboratory, SC. Telephone: 803-725-5948, Email: brian.riha@srnl.doe.gov

  - Joseph Rossabi, Redox-Tech, Inc. Telephone: 919-678-0140, email: rossabi@redox-tech.com

  - Karen Vangelas, Environmental Science and Biotechnology Section, Savannah River National Laboratory, SC. Telephone: 803-725-5223, Email: Karen.vangelas@srnl.doe.gov

2.0 TECHNOLOGY DESCRIPTION

2.1 Theoretical Basis

2.1.1 Barometric Soil Vapor Extraction

Fluctuations in the atmospheric pressure transmit through the soil as pressure waves that attenuate and decelerate with depth and lower soil permeability. This damping and delay effect results in a sustained period of time during which the surface and subsurface pressure are not in equilibrium. As a result, when the two zones are directly connected (as through a well), there is a dynamic flow of air from the zone of high pressure to the zone of low pressure (Figure 2.1), a process known as "barometric pumping". When the atmospheric pressure is greater than the subsurface pressure, ambient air flows into the well. This principal forms the basis of passive bioventing technologies that are used to deliver oxygen/air to soils impacted with petroleum hydrocarbons. Exhalation or venting of soil gas, which forms the basis for PSVE, occurs when the subsurface pressure is greater than the atmospheric pressure.

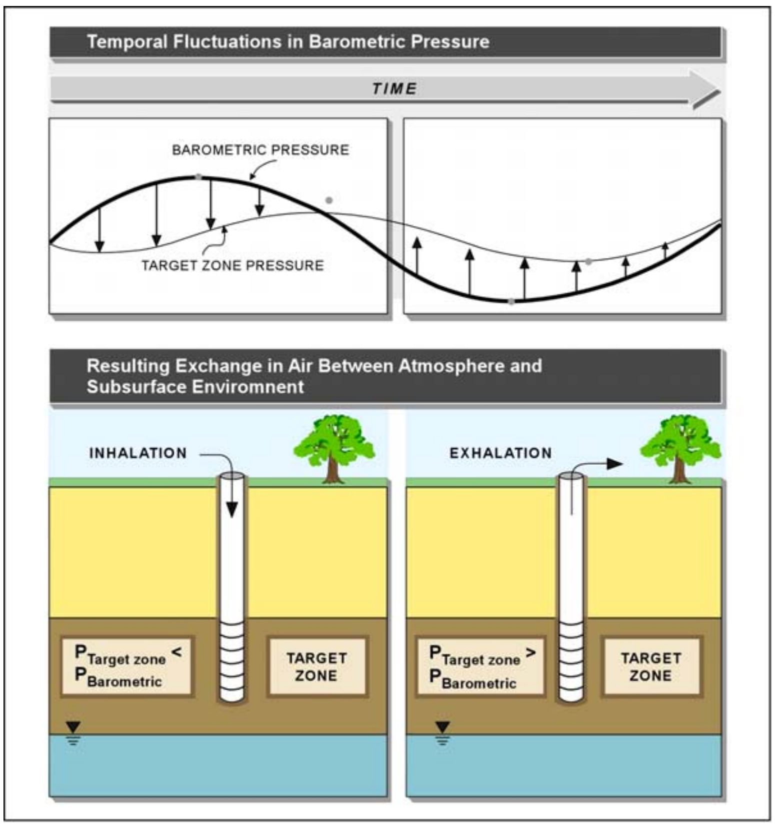


Figure 2.1: Conceptual Model for the 'Inhalation' and 'Exhalation' Phenomenon Observed in Wells Installed within the Vadose Zone.

The *mass flux* of contaminants from an extraction well (kg/yr) depends primarily on the radial permeability within the target zone and on the magnitude of the pressure gradient that develops between the atmosphere and the target zone. The pressure gradient in turn is a function of the lithology and the vertical permeability of the soil layers overlying the target zone. At sites with deep vadose zones or with a highly stratified soil structure, the damping phenomenon can be substantial, resulting in differential pressures that are sufficient to induce high soil gas or ambient air flow rates. Sites with more resistance to vertical air flow (due to man-made caps or from natural “confining” units) will show higher differential pressure and sometimes higher flowrates from barometric SVE applications. During outflow events, the soil gas flow can remove accumulated volatile contaminants released from impacted soils. At the MAPSL site (Riha, 2005c), soil gas flow rates up to 76 cubic feet per minute (cfm) have been recorded in extraction wells screened within the vadose zone during exhalation or venting (Figure 2.2). Apart from fluctuations in pressure, PSVE well vapor flows are a function of well size, screen length, screen zone and gravel pack. Larger wells (e.g. 4-inch diameter wells) generally produce higher amounts of flow compared to 2-inch diameter wells (Rossabi, 1999). Refer to Appendix A for predicting values of contaminant mass flux and predicted soil gas flow rates based on measured contaminant concentration in the soil gas and estimated values for vertical and radial permeability for the site.

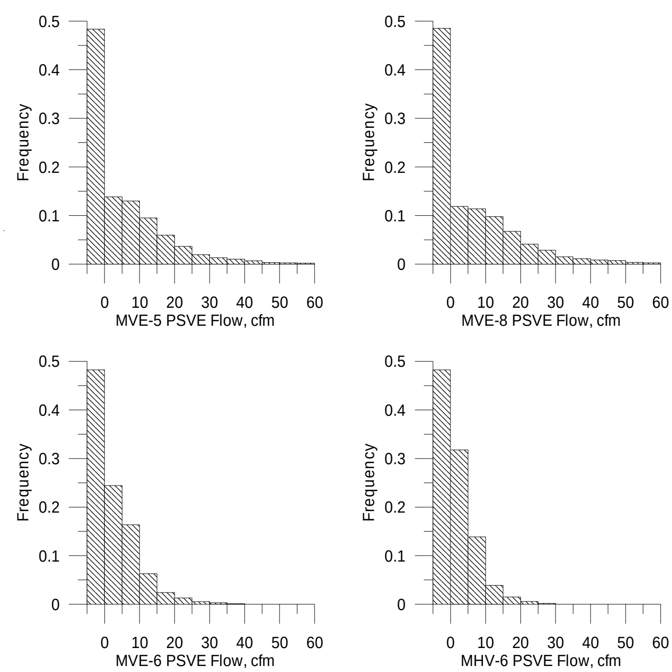


Figure 2.2: Distribution of Flow Rates from an Extraction Well collected at 15 Minute Intervals over a Period of One Year (adapted from Riha, 2005c).

The *duration of flow* depends on the relative frequency of fluctuations in the atmospheric pressure and the attenuation capacity of the unsaturated zone overlying the screened interval. Atmospheric pressure fluctuations occur on a diurnal as well as on a seasonal basis. In areas within the contiguous United States, the diurnal atmospheric pressure fluctuations can range between 0.3 to 6 inches of water, with pressure highs observed in the early morning and lows in the afternoon (ESTCP, 2006). Weather-front atmospheric pressure changes, on the other hand, typically last 3 to 5 days and can be of a significantly higher magnitude than the diurnal fluctuations (Neeper, 2002). Typical diurnal changes in the barometric pressure are shown in Figure 2.3.

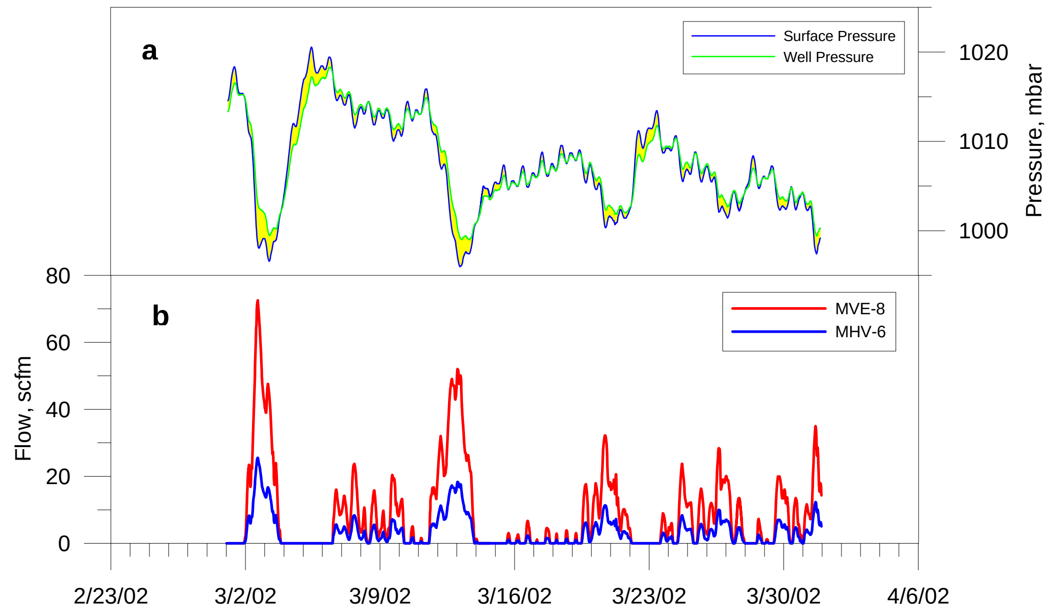


Figure 2.3a: Typical Diurnal Changes in the Barometric and Subsurface Pressure at an SRS site, SC. b. Typical Daily Flow Rates Measured in Extraction Wells Undergoing Barometric Pumping at an SRS Site, SC (adapted from Riha, 2005c).

The pressure wave attenuation capacity of a site can also affect the duration of the equilibration period and is a function of the depth and vertical permeability of the vadose zone. Deep vadose zone contamination (Figure 2. 4), low permeability strata between surface and target zone, or presence of a surface seal (as utilized in BERT^{TM} applications) can extend the equilibration period resulting in longer exhalation responses.

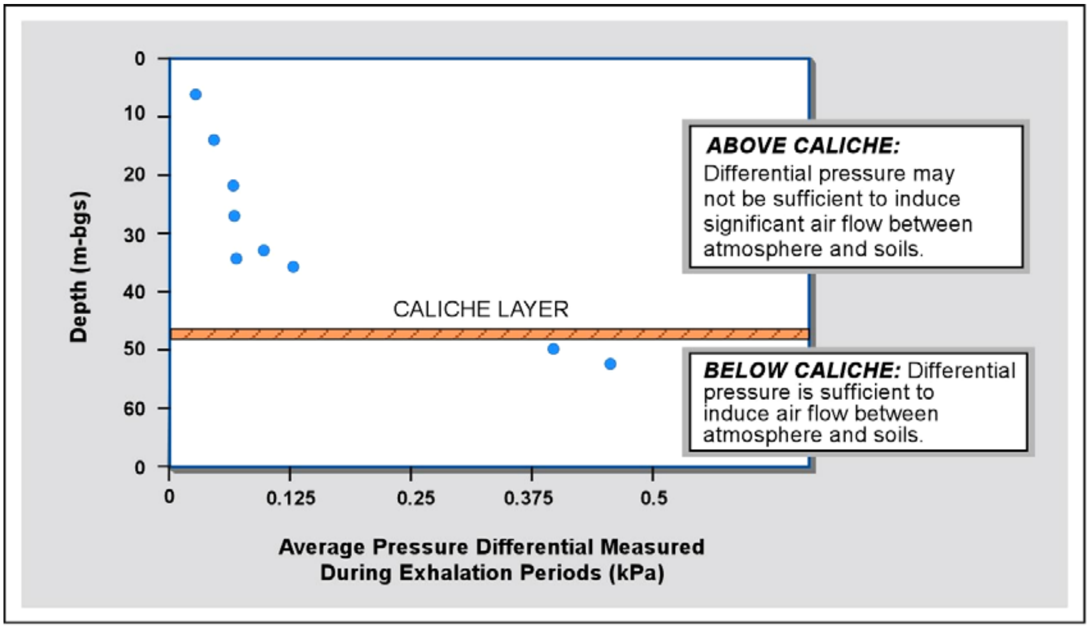


Figure 2.4: Average Differential Pressure Measured Above and Below a Low Permeability Caliche Layer at the Hanford Site, WA (adapted from Rohay et al., 1997)

The *radius of influence* (ROI) of a barometric application is a function of the soil permeability and the pressure gradient (Rohay et al., 1997). At the INEEL site in Idaho, tracer tests using sulfur hexafluoride were used to estimate the ROI (7 m). At the SRS sites, an ROI of 4 – 5 m was estimated using a simple cylindrical model of well capture. At the Hanford site, the ROI was calculated using the same method and was found to range between 15 – 24 m, due to lithological controls (very high permeability strata) that increased the effectiveness of the pressure-difference induced flow.

The mass of contaminants removed depends on the soil gas extraction rate and the concentration of contaminants in the soil gas. Installation of one-way passive valves has been shown to prevent the dilution of soil gas with ambient air during the “inhalation” periods, resulting in at least two times the mass removal rates achievable without the control valves (Rohay et al. 1997; Rossabi, 1999).

2.1.2 Assisted Passive Soil Vapor Extraction

Due to its reliance on the pressure gradient between the atmosphere and the subsurface, barometric pumping may be unsuitable for sites with very shallow contaminated soils. At these sites, contamination is often confined to low permeability strata or there isn’t sufficient cumulative vertical flow impedance to produce adequate pressure difference periods between the surface and target zones. For such sites, small blowers can be used as part of an “assisted PSVE” system to exert a continuous and consistent soil gas extraction rate at the extraction well. The blowers are low-cost and are capable of operating using renewable energy sources such as solar or wind power. By using renewable sources of energy, the blowers eliminate the need for an external power supply that would require consumables (e.g., gasoline, diesel, propane, etc.) and ancillary infrastructure that are generally required to run conventional ASVE systems in remote areas, thereby reducing the carbon footprint and O&M expenses.

As with ASVE systems, the amount of soil gas extracted is a function of the radial permeability of the target zone, the vacuum application rate, the volume of the target zone, and the air handling capacity of the blower. Furthermore, large diameter wells produce slightly more soil gas than smaller wells. The ROI depends on the radial permeability of the target zone, presence of stratigraphic or man-made features that constrain the target volume, and the applied vacuum. Based on typical ROI estimates for ASVE systems (4 m to 30 m) (Johnson et al., 1990), the maximum ROI that can be expected from an assisted PSVE system is likely to be less than 30 m.

2.2 Description of Equipment

2.2.1 Barometric Applications

Researchers have developed an array of check valves that can be used in barometric applications. Of these, only the BaroBall™ control valve is available commercially.

a. *BERT™ Mylar Flapper Valve*: The valve was designed by researchers at Science and Engineering Associates and installed at the INEEL Radioactive Waste Management Complex in December 1996 to promote barometric extraction of volatile organic compounds (VOCs) at the site (ITSER, 2000). The design was later installed at the Los Alamos National Laboratory (LANL) site in 1999 to vent accumulated water vapor from beneath asphalt pads in a radioactive waste storage area.

   The assembly includes a light-weight flapper valve, mounted at an angle, inside a stack vent (Figure 2.5). The valve is a low-differential pressure relief valve with a cracking pressure (i.e., the amount of pressure required to open the valve) less than 0.1 mbar. Under negative pressure differential conditions, the valve maintains a seal thus preventing flow of ambient air into the stack. Additionally, the assembly includes a turbine ventilator that enhances soil gas removal under high wind speed conditions. The device was originally designed to be installed directly within a surface seal (such as a geosynthetic liner), however, a similar assembly can be easily constructed and fitted directly to extraction wells.

b. *INEEL Mylar Disk*: The disk was originally designed at the Idaho National Engineering and Environmental Laboratory (INEEL) and is currently used at a few sites in Denmark. Like the mylar flapper valve, the mylar disk has a low cracking pressure and is capable of maintaining a seal during negative pressure differential conditions.

c. *Baroball™ Control Valve*: Designed by scientists at Savannah River National Laboratory, the Baroball™ uses a table tennis ball placed in a valve seat to allow flow of soil gas into the atmosphere when the pressure in the well is greater than the atmospheric pressure and seals the well by closing the valve when the atmospheric pressure is greater than the pressure in the well. In the currently available model, the cracking pressure is less than 1 mbar. A version of the Baroball was designed to facilitate the measurement of the volume of air passing through the valve using a tapered column that permits the ball to rise in the column in proportion to the flow rate. Furthermore, an in-line condenser located between the well and the valve prevents moisture condensation in the valve that could cause it to freeze in one position during cold weather. The condenser also holds condensed water that is produced when warmer, moist air from the subsurface is cooled in the valve tubing during cold weather. The condensate can be drained periodically with a valve in the bottom of the condenser.

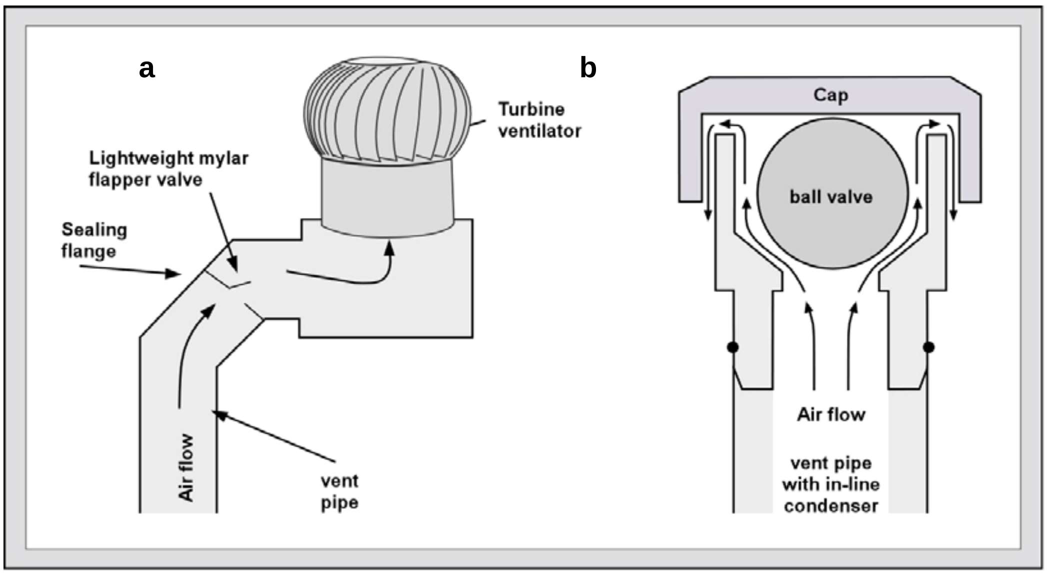


Figure 2.5: Schematic of Control Valves used in Barometric Applications a. BERT™ Flapper Valve (ITSER, 2000) b. Baroball™ Control Valve

2.2.2 MicroBlower Applications

The MicroBlower system is simple and easy to install on individual wells. The assembly consists of a 12- or 24-V DC vacuum blower powered by a renewable energy source such as solar or wind energy. A battery bank can be used for reserve power when sun or wind is inadequate. The blower pumps in the system are small and unobtrusive, measuring 4 inches in height and 3 inches in diameter. Currently-available MicroBlowers are capable of generating a maximum vacuum of 10.2 inches-water and handling maximum air flow rates of 17-18 standard cubic feet per minute (scfm) (see Figure 2.6). The blowers are also fitted with Baroball™ control valves to ensure unidirectional flow of air. The blowers can be designed to operate 24 hours/day and are rugged with mean time between failures (MTBF) on the order of 15,000 to 20,000 hours.

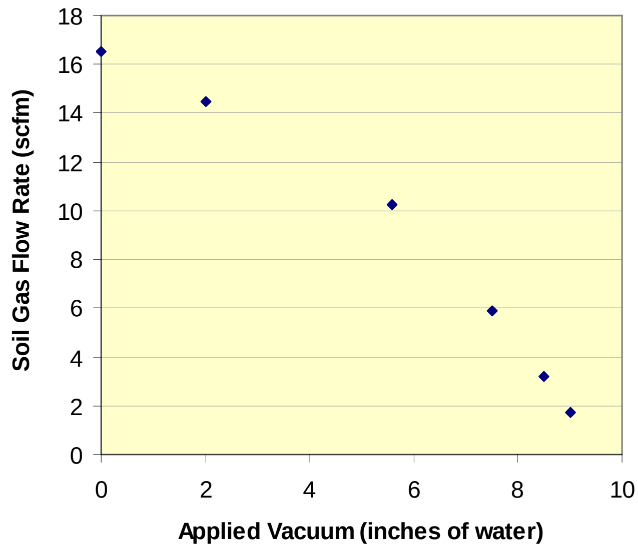
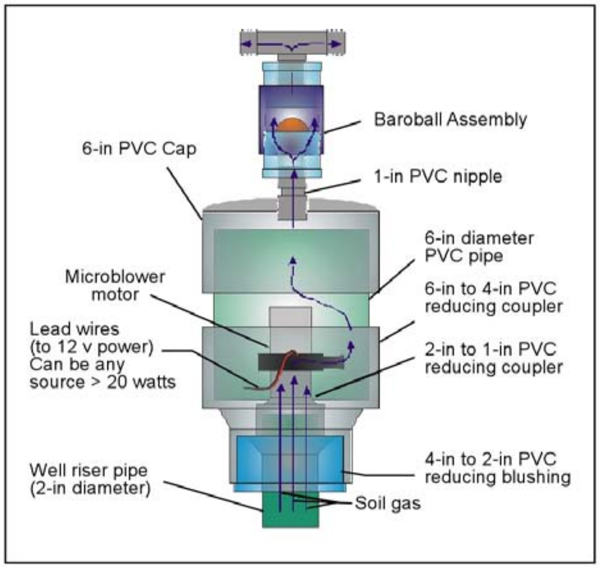


Figure 2.6: Measured Pump Curve for the MicroBlower used at SRS, SC.

a



b

Figure 2.7: (a) Schematic of the MicroBlower Assembly; (b) MicroBlower installed at an individual well at an SRS site, SC.

2.3 System Operation and Maintenance

2.3.1 Barometric Applications

The one-way passive valve is a simple mechanical device that requires minimal maintenance over the long-term apart from periodic inspections to ensure proper sealing of the valve when closed and easy opening during outflow pressure events. Presence of dirt or insects can interfere with the sealing of the ball/flapper and result in some leakage of ambient air into the well during inflow events. In general, this condition corrects itself during subsequent outflow events.

2.3.2 MicroBlower Applications

The MicroBlower assembly requires basic house-keeping to ensure effective long-term operation - cleaning of the pumps, dusting of the solar panels or maintenance of the wind generators. Current field experience with systems using solar panels as the energy source indicates that the O & M requirements for the MicroBlowers are minimal.

2.4 Long-Term Monitoring for PSVE Applications

In general, an effective SVE monitoring program should involve periodic collection of data necessary to estimate contaminant mass flux as well as evaluate the progress of remediation by SVE. Mass flux (units - kg/yr) can be calculated based on field measurements of the soil gas extraction rates and VOC concentrations in the extracted gas. Remedial progress within the zone of influence of the extraction well can be estimated using results from a rebound test performed at regular intervals during the course of the SVE program. See Site Example 1 in grey box for a description of the method used at the MAPSL site, SRS, SC to demonstrate the effectiveness of a PSVE application.

2.4.1 Estimation of Contaminant Mass Flux

The average contaminant mass flux (kg/yr) can be calculated by multiplying the average VOC concentrations measured in the extracted soil gas by the estimated average soil gas flow rates.

Measurement of VOC Concentrations in Soil Gas: Field equipment capable of measuring both the VOCs and CO_2 e.g. Infra-red Photo-Acoustic Spectroscopy (IRPAS) should be used in order to determine the average VOC concentrations in the soil gas. Measuring the CO_2 concentrations in the extracted soil gas is necessary to ensure that extracted gas is from the subsurface target zone and is not being short circuited from the surface. Alternatively, samples may be collected in Tedlar bags, summa canisters or glass vials and analyzed using standard methods.

Measurement of Soil Gas Flow Rates: Due to the intermittent nature of the barometric pumping technology, the use of continuous flow data logging systems to measure soil gas flow within the vent well is generally recommended for at least some wells in a barometric extraction system. Wells must be temporarily sealed to accurately measure the subsurface pressure. Once the relation between surface pressure fluctuations and subsurface pressure (and ultimately flow through the well) have been established by monitoring, the flow response to surface pressure fluctuations can be accurately predicted by analytical models (Rossabi and Falta, 2002).

Measurement of soil gas extraction rates in MicroBlower applications are identical to those used in conventional ASVE applications. Since the flow rates tend to be more consistent than barometric applications, weekly measurement of the instantaneous soil gas flow rate at the wellhead using a hand-held thermal anemometer should satisfy the data requirements. If the MicroBlowers are operated without a power storage mechanism (e.g. a battery), then the operating history of the renewable energy power system will determine the volume of gas extracted.

2.4.2 Evaluating Remedial Progress within the ROI

A rebound test is a widely-accepted method for estimating the extent of progress of an SVE remedial program.

The premise of a rebound test is that soils are heterogeneous and flow of soil gas towards an extraction well occurs as a result of *rapid advective flow* from the more permeable soil layers surrounding the well. Contaminant transport from soils with relatively low permeablility, on the other hand, is dictated by the rate of contaminant *diffusion* from the low permeability soils to the more permeable soils, a process that may occur over periods of months or years. As a result of this difference in timescale for contaminant transport, the VOC concentrations in the extracted soil gas rapidly declines during the early stages of SVE operation, reflecting the rapid flushing of the VOC-laden soil vapor within the more permeable zones. However, the concentration ultimately stabilizes over time at a rate that reflects the rate of diffusion of the contaminant from the low permeability soils. The concentration of VOCs during the latter stages of an SVE operation is therefore an indicator of the progress of the remediation and can be used to predict the flux of contamination to determine risk to receptors and appropriate mitigation strategies.

a

b

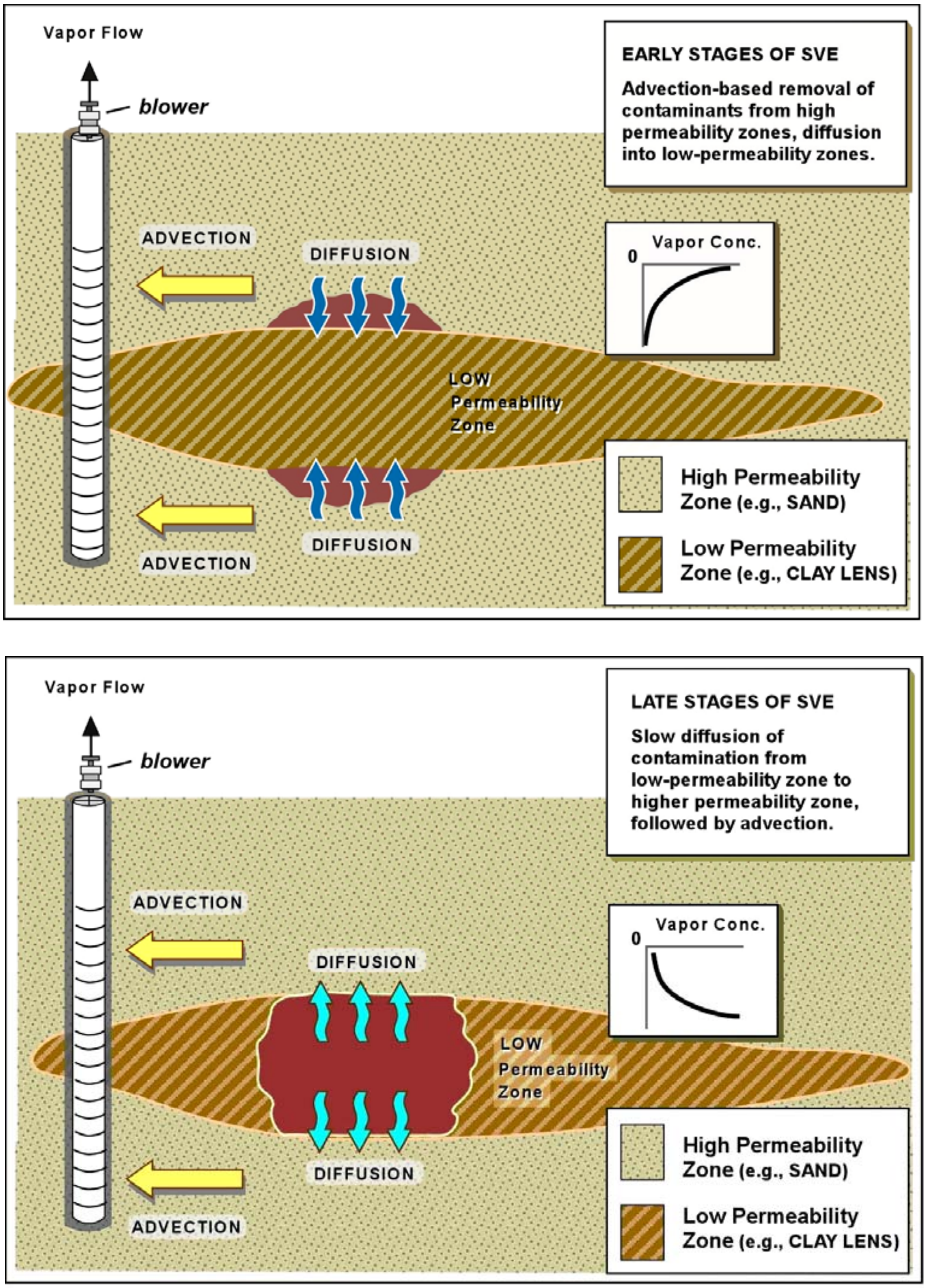


Figure 2.8: Schematic of Advective and Diffusive Flow of Soil Gas during a. Early and b. Late Stages of Soil Vapor Extraction.

During a rebound test, the operating SVE system (barometric or MicroBlower) is shut-off to allow the different soil layers to equilibrate. Over time, the concentration of VOCs in the more permeable layers should "rebound" at a rate that is dictated by *diffusion* processes within the low permeability soils. This maximum or equilibrium concentration achieved in the extraction well during the rebound test can be used to qualitatively predict the residual mass of contaminants remaining in the source zone. For more details on how to conduct a rebound test, refer to the USACE SVE design guide (2002). Site example 1 (shown in grey box) describes a method used at the MAPSL site (Riha, 2005c) to evaluate long-term performance effectiveness of a barometric strategy. This same strategy can be used to calculate performance objectives for a future PSVE strategy as well.

SITE EXAMPLE 1: COMPARISON OF MASS REMOVAL RATES TO MASS TRANSFER RATES IN THE TARGET ZONE AT THE MAPSL SITE, SRS, SC

Site: In 2005, a rebound test was conducted using five inactive ASVE wells at the M-Area Abandoned Process Sewer Line (MAPSL) at the Savannah River Site, SC. These wells were screened in or very close to three fine-grained zones containing residual VOCs. Data collection included periodic analysis of soil gas for PCE and TCE concentrations.

In addition, two nearby inactive ASVE wells, not included in the rebound test, were fitted with the Baroball™ assembly and measured for continuous flow rates and soil gas concentrations.

Performance Metric: In order to reduce the migration of contaminants to groundwater, a PSVE system should be capable of extracting VOC mass at a rate that equals or exceeds the rate of mass transfer of contaminants from contaminated soils within the target zone to soil gas phase.

Data Analysis: The mass transfer rate of VOCs in the soils surrounding each well was obtained by calculating the slope on a linear fit applied to the initial concentrations measured at each well during the rebound test. These estimates were then scaled to obtain the VOC mass loading to the entire source zone area.

The average VOC mass removal rates were calculated using soil gas flow rates and VOC concentrations in the soil gas extracted from the two inactive ASVE wells fitted with the Baroball™ assembly. These estimates were then scaled to obtain total VOC mass removal in the source zone area.

Results:

- ***PCE:*** Mass loading of PCE from the source area was calculated to be approximately 0.024 kg- PCE/day (8.8 kg-PCE/yr) whereas the measured mass removal rates by barometric pumping was approximately 0.03 lbs-PCE/day (11.6 kg-PCE/yr)

- ***TCE***: Mass loading of TCE from the source area was approximately 0.022 kg-TCE/day (8.0 kg-TCE/yr). In contrast, the actual mass removal rates by barometric pumping was measured to be approximately 0.027 lbs-TCE/day (9.95 kg-TCE/yr).

Site Example 1 Conclusion: The PSVE technology was shown to be effectively removing mass from the source zone at rates greater than the rates of dissolution or diffusion and therefore, the technology was considered protective of the groundwater at the Site.

2.5 Site Transition to MNA

The ultimate goal for any PSVE site is to eventually transition to MNA and/or site closure. Determining specific criteria that can predict when this transition can be made is essential and should be identified early-on in the site decision-making process by site stakeholders. Depending on site conditions and identified remediation drivers, a site could have requirements other than generic MCLs to meet the “no further action” level. This allows for development of innovative site-specific metrics that can be used to support this transition. See Site Example 2 (grey box) for description of one of the site transition goals developed for the MAPSL site at the SRS, SC (Riha and Whiteside, 2008).

SITE EXAMPLE 2: SITE TRANSITION CRITERIA AT THE MAPSL SITE, SAVANNAH, SC

At the MAPSL site, a risk-based site specific target level (SSTL) was proposed as the transition point from a PSVE to an MNA strategy. Simple partitioning equations were used to determine the maximum soil vapor concentration of each contaminant that could exist in equilibrium with impacted pore water in a source zone without posing any additional risk to groundwater due to leaching.

First, a pore water concentration protective of the groundwater was calculated by dividing the lowest concentration measured in on-site wells by a safety factor of 10. At the site, the lowest concentration of PCE and TCE measured was 0.6 mg-PCE/L and 1.6 mg-TCE/L. Based on a safety factor of 10, the pore water concentration considered protective of the groundwater was assumed to be 0.06 mg-PCE/L and 0.16 mg-TCE/L.

Next, the soil vapor concentration in equilibrium with the pore water was calculated under equilibrium conditions using Henry’s Law. This soil vapor concentration was considered to be protective of the groundwater. At the MAPSL site, the soil vapor SSTL for PCE and TCE was calculated to be 4.7 ppmv-PCE and 9.3 ppmv-TCE and was therefore, proposed as a potential end-point for the PSVE strategy.

3.0 TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Given the complex distribution and migration patterns of contaminants at chlorinated solvent sites, successful strategies for clean-up often involve a combination or a sequence of technologies that address different site conditions as the treatment progresses. Prior knowledge of the strengths and weakness of any technology, as well as any potential compatibility issues, is key when considering combined remedies to ensure that a remedial configuration for a site will be optimally effective.

3.1 PSVE Technology Strengths

The primary advantages of PSVE applications are their technological *simplicity*, *cost-effectiveness* and wide *applicability*.

- PSVE systems are most effective at removing residual concentrations of volatile contaminants from the unsaturated zone. It is therefore suitable as a polishing technology for sites where ASVE performance no longer warrants its operating costs. For example, at sites where the VOC transport in the vadose zone is dictated by *diffusion* mechanisms, the intermittent nature of barometric pumping can ensure that the available contaminant mass will be removed as it is released from the low permeability zones and at a price that ASVE or other active technologies cannot match.

- Like conventional SVE strategies, the technology exhibits the highest gas removal rates in coarse soils with high permeability, but because of the passive nature of the technology, it is also applicable to diffusion-controlled, lower permeability soils. For barometric pumping, the presence of multiple soil layers separated from the atmosphere by a confining unit or by depth greatly increases the effectiveness of the technology. For assisted PSVE, good conditions for solar or wind power increase the overall effectiveness.

- Due to their minimal operating and maintenance requirements, PSVE technologies such as the Baroball™ and MicroBlower systems are well-suited for application at remote sites.

- The Baroball™ and MicroBlower systems use conventional, readily-available supplies and construction techniques.

- Capital costs for PSVE technologies are low. Units for individual wells range up to \$1300 – \$2000 per well for small vacuum blowers (including power sources), and < \$50 per well for barometric pumping equipment.

- Installation and operation of a PSVE well network does not create major site disruptions. Additionally, at sites with an existing ASVE well network, it is possible to convert ASVE wells to PSVE wells by installing appropriate venting valves or motors.

- Implementation of either system eliminates the need for costly and high-maintenance infrastructure typically associated with an ASVE application, such as high power electric blowers, vacuum manifold systems and electrical lines and control boxes.

- Operating and maintenance costs are generally low and the units can be expected to operate continuously for the life span of the remediation with little or no intervention.

3.2 PSVE Technology Weaknesses

In general, PSVE technologies suffer from the same limitations as those documented for ASVE, but with the additional limitation that the removal rates and radius of influence for extraction wells will likely be lower than ASVE applications.

- SVE technologies are limited to vadose zone contamination and do not directly address existing groundwater contamination in most situations.

- High moisture levels or high pore water saturation can limit air permeability and reduce the rate of contaminant mass removal.

- The presence of preferential pathways, such as abrupt changes in lithology, deep root zones, or anthropomorphic features, could result in low air flow due to vacuum disruptions or more likely, short-circuiting to the atmosphere.

In addition to these limitations,

- PSVE technologies are typically not appropriate to treat high levels of VOCs in comparison with ASVE. High contaminant mass removal rates would probably necessitate above-ground vapor treatment which may off set the benefits of a low-energy extraction system. Furthermore, it would be harder to gain regulatory approval for a passive treatment technology at these sites when an active remediation technology would probably be more effective in terms of mass removal rates.

- Low and intermittent extraction of air at sites employing barometric pumping may not be sufficient to meet the target mass removal rates. Depending on the site lithology and barometric pressure gradient, peak flow rates may be as low as 1 cubic foot per minute (cfm), and may last only a short period during each 24-hour period. For sites employing solar- or wind-powered SVE, the highest vacuum possible still may not produce desirable airflow rates.

- Barometric pumping is generally not suitable for sites with limited lithologic stratification or a shallow groundwater table. These factors allow vertical movement of air from the surface, which circumvents the barometric pumping process.

- Due to the small zone of capture around each well, sites employing PSVE technologies may generally require more extraction wells than conventional active SVE systems, thus adding to the overall cost of site preparation, installation and monitoring. In some cases, additional wells may be needed to convert an active SVE system to a PSVE system.

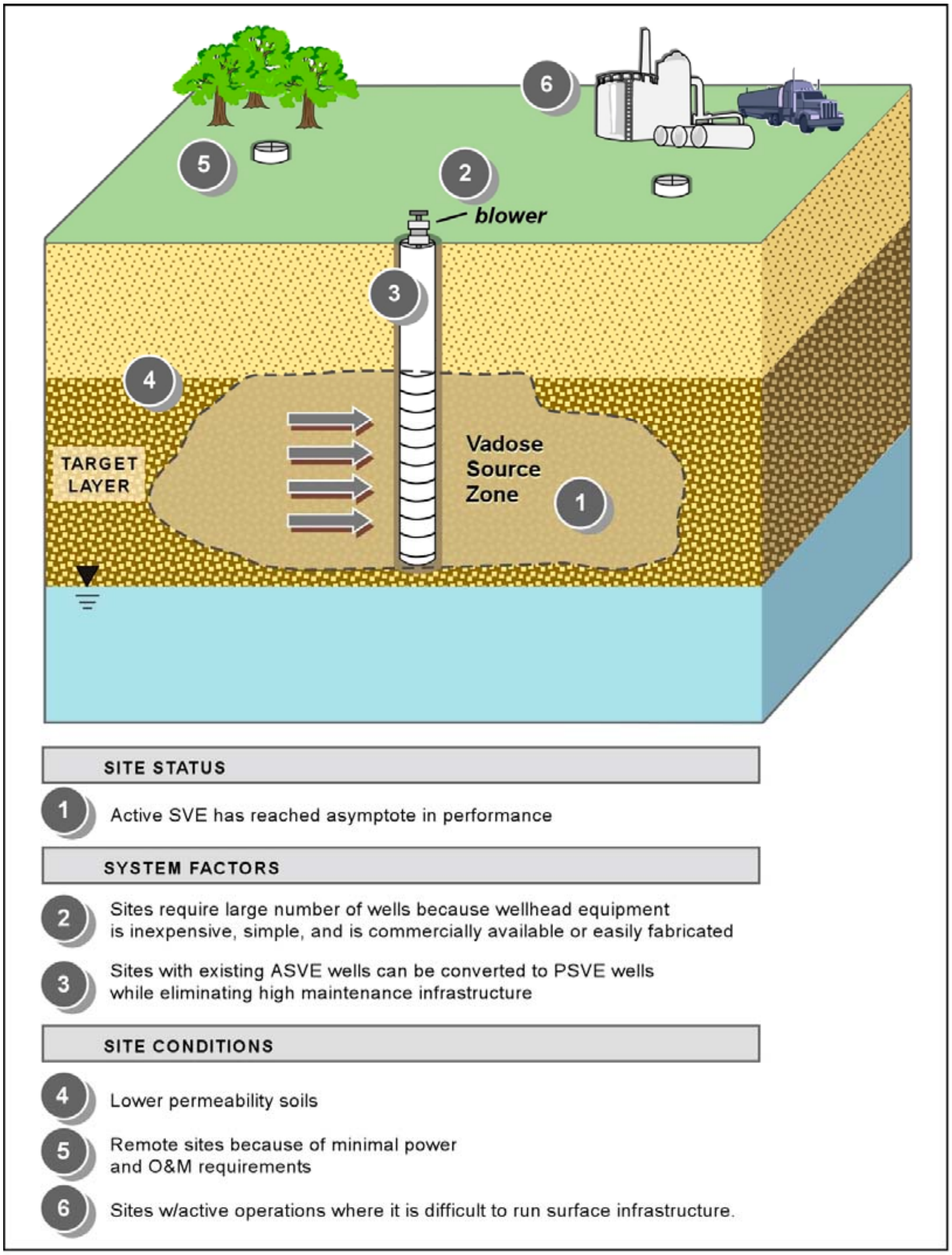


Figure 3.1a: Factors that Favor PSVE.

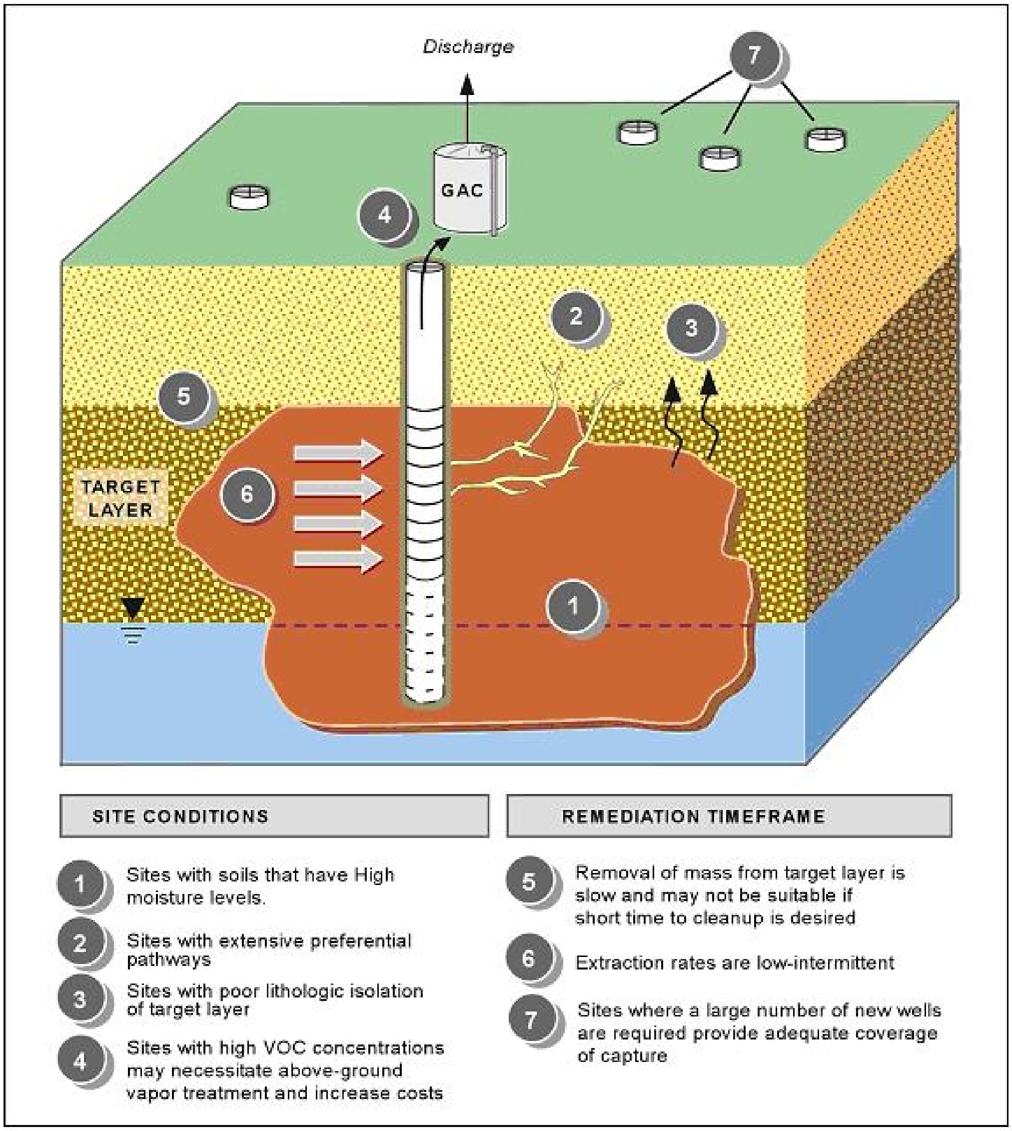


Figure 3.1b: Factors that could Preclude PSVE.

3.3 Competing and Complementary Technologies

PSVEs are technologically simple and do not require modifications to the hydrological flow or to the natural aquifer characteristics to be effective. Therefore, the selection of PSVEs does not restrict the choice of technologies that can be implemented subsequent to a PSVE application. However, active technologies that alter aquifer conditions (i.e., reduce the porosity and/or the air permeability of the unsaturated zone) can negatively impact the effectiveness of any concurrent or subsequent PSVE application. Potential compatibility issues that can arise between PSVEs and other technologies routinely evaluated at chlorinated solvent sites are shown in Table 3.1.

Technologies that are compatible with concurrent or subsequent PSVE applications include most saturated zone treatment technologies such as *bioremediation* and *phytoremediation*, which can be deployed in the vicinity of a PSVE well network without concerns about reducing the effectiveness of either technology.

Infiltration barriers or *capping technologies* can increase extraction efficiencies of barometric pumping wells. As an impermeable barrier, the surface seal allows for development of greater pressure differentials between the surface and the target zone, thus enhancing soil vapor gas flows from the subsurface. Furthermore, by restricting infiltration into the vadose zone and by reducing the likelihood of short-circuiting to the atmosphere, the surface barrier serves to increase the efficiency of any concurrent PSVE application.

On the other hand, active source remediation technologies such as *thermal treatment* and *surfactant flushing* can decrease the effectiveness of any subsequent SVE technology. By reducing the overall gas filled porosity and/or permeability of the treated aquifer, such technologies can interfere with VOC mass transport within the soil. At sites where an active SVE system is still in place, installation of a PSVE well near an ASVE wellhead could render the PSVE well ineffective if the zones of capture for the two wells overlap.

Saturated zone pump and treat (P&T) can increase extraction efficiencies of PSVE in areas of groundwater table drawdown and reduce extraction efficiencies of PSVE in re-injection areas of groundwater table mounding. Impacts to the water table effectively increase or decrease the depth of the vadose zone, resulting in higher or lower extraction rates, respectively, by any concurrent SVE application.

Table 3.1: Remedial Technologies Routinely Employed at Chlorinated Solvent Sites and Potential Compatibility Issues that can arise during Concurrent or Subsequent PSVE Applications

Remedial Technologies Routinely Employed at Chlorinated Solvent Sites	Potential Impact on Source and/or Groundwater Plume	Potential Impact on Concurrent or Subsequent PSVE Applications within Treated Zone		Rationale for Compatibility Status
		Compatible/ Complementary	Competing / Possibly Non-Compatible	
Source Enhancement Zone Technologies				
• **Excavation**	Source mass removal	✓		Reduced mass could encourage selection of PSVEs.
• **Soil Vapor Extraction**	Source mass removal	✓	✓	Compatible as a precursor to PSVE. Could be a competing technology if concurrently implemented. High vacuum rates could interfere with the development of a diffusion gradient between the passive well and surrounding areas
• **Thermal remediation (Electrical Resistance)**	Source mass removal & mass flux reduction		✓	Potential reduction in porosity and air permeability could affect soil gas flow rates and VOC diffusion kinetics
• **Thermal remediation (Steam injection)**	Source mass removal & potential for mass flux reduction		✓	Potential reduction in porosity and air permeability could affect soil gas flow rates and VOC diffusion kinetics
• **Flushing (surfactants, foams, cosolvents)**	Increases mass flux of contaminants from low permeability zones		✓	Reduction in permeability could affect VOC diffusion rates and air flow rates
• **Chemical Oxidation (In Situ Oxidation)**	Reduction in source mass and mass flux	✓		No interference foreseen
• **Capping/Infiltration Barriers**	Reduced infiltration resulting in decreased mass flux of contaminants from treated zone	✓		Surface seal could increase the pressure differential between the atmospheric and subsurface. Also, lower infiltration through the source could reduce moisture content in the vadose zone.

Remedial Technologies Routinely Employed at Chlorinated Solvent Sites	Potential Impact on Source and/or Groundwater Plume	Potential Impact on Concurrent or Subsequent PSVE Applications within Treated Zone		Rationale for Compatibility Status
		Compatible Complementary	Competing / Possibly Non-Compatible	
Source Enhancement Zone Technologies (CONTD.)				
• **Dual Phase Extraction**	GW and vadose zone mass removal	✓	✓	Could be a competing technology if proper precautions to prevent mounding are not taken. Also, if re-injection is permitted at the site, care should be taken not to re-inject in the vicinity of any active PSVE wells.
• **Addition of bio substrates as Vadose Zone Application**	Decrease mass flux to the groundwater	✓	✓	Could enhance biodegradation of contaminants within the vadose zone. However, it is possible that the added substrate could likely decrease permeability and gas filled pore volume.
Plume Enhancement Zone Technologies				
• **Pump & Treat**	Dissolved mass removal	✓	✓	Could be a competing technology if proper precautions to prevent mounding are not taken. Also, if re-injection is permitted at the site, care should be taken not to re-inject in the vicinity of any active PSVE wells.
• **Slurry wall**	Decreases Contaminant Mass Flux from submerged source	✓		No interference foreseen
• **Air Sparging**	Assists in source mass removal	✓		Could enhance mass transfer of VOCs, however, technology is energy-intensive and not sustainable. Therefore, implementation would defeat the purpose of PSVE.
• **Bioremediation (e.g. Engineered addition of Electron Donors)**	Dissolved mass removal	✓		No interference foreseen
Discharge Enhancement Zone Technologies				
Phytoremediation	Dissolved mass removal	✓		No interference foreseen

4.0 TECHNOLOGY PERFORMANCE

The performance of PSVE at several sites is summarized in the following section. In all cases, conditions at these sites were judged suitable for application of PSVE, either as a stand-alone measure or following (or in conjunction with) ASVE. Performance was assessed using most of the measures outlined in Section 5 of this document (concentration reductions, mass removal. etc.). Note that while the majority of the data is from applications using barometric pumping, a site where assisted PSVE using a MicroBlower device is also included.

4.1 Metallurgical Laboratory (Metlab)

4.1.1 Site Description

The Metallurgical Laboratory (MetLab) waste unit is located at the Savannah River Site (SRS), within the A/M areas. PCE and TCE were the primary solvents used at the site, with historic releases leading to vadose zone soil impacts and the development of a soil gas plume. Nineteen vadose zone wells were installed across the source area of the Metlab in 1996 and BaroBall^{TM} devices were installed at the surface of each well casing to permit passive soil vapor extraction via natural barometric pressure changes. Monitoring of well vapor concentrations (PCE and TCE) began in June 1998 and continues to present day.

Site characteristics that contributed to the selection of PSVE:

- Vadose zone source is well-defined and present in deep, lithologically isolated strata
- Need for cost-effective, low-maintenance treatment that protects the groundwater

4.1.2 Results/Performance Metrics

Performance data for the Metlab is available through June 2005 (Riha, 2005b) and includes temporal concentration trends, mass removal rates, plume size, and cumulative mass removal, as summarized in Table 4.1.

Table 4.1: Results from Full-Scale Application of Passive Soil Vapor Extraction at the MetLab Site, SRS, SC.

Site Name	***MetLab***
Location	Savannah River Site, Aiken, SC
Type of Device Utilized	Baroball™
No. of Wells	19
No. of Wells per acre	~ 6 (estimated)
Zone of Capture	~ 25 (assumed based on well spacing)
Screened Interval	60 ft (from 20 to 80 ft bgs)
Average Flow Rate	1 cfm
Pore Volumes Removed During Operating Period	Not reported
Starting Vapor-Phase Concentration	18.0 ppmv PCE 15.4 ppmv TCE (Average of 19 wells)
Ending Vapor-Phase Concentration	0.8 ppmv PCE 0.7 ppmv TCE (Average of 19 wells after 7 years of operation)
Mass Transfer/Removal Rate (per well)	0.0006 to 0.0020 yr^{-1} PCE 0.0004 to 0.0016 yr^{-1} TCE
Mass Removed (per well)	0.3 to 11.4 kg of PCE; 0.09 to 8.8 kg of TCE
Mass Removed (cumulative)	74.3 kg of PCE; 48.6 kg of TCE
Cost	Not reported

4.2 Miscellaneous Chemical Basin (MCB)

4.2.1 Site Description

The MCB waste unit is located in the northwest portion of the Savannah River Site. Limited information is available concerning historic releases within the MCB, but it is thought that the basin received mixed solvent waste, used oil, and partially full drums until 1974. These historic releases led to vadose zone soil impacts and the development of a soil gas plume (with the center of the plume not corresponding to the former location of the basin due to regrading). Twenty-five vadose zone wells were installed across the source area of the MCB in 1996 (Figure 4.2) and Baroball™ devices were installed at the surface of each well casing on each well casing to facilitate passive soil vapor extraction due to natural barometric pressure changes. Monitoring of well vapor concentrations (PCE and TCE) began in April 1996 as part of a treatability study that extended for a period of approximately 1 year. Based on the success of this initial study, the system was left in place and continues to operate through present day. An active soil vapor extraction system was also operated between October 2001 and December 2002.

Site characteristics that contributed to the selection of PSVE:

- Vadose zone source is well-defined and present in deep, lithologically isolated strata
- Need for cost-effective, low-maintenance treatment that protects the groundwater

4.2.2 Results/Performance Metrics

Comprehensive performance data for the MCB is available from the treatability study (Riha and Rossabi, 1997) and includes temporal concentration trends, mass removal rates, plume size, cumulative mass removal, and estimation of remediation timeframe, as summarized in Table 4.2. It should be noted that the operation of an ASVE system at the MCB influenced the performance of the PSVE after this period, such that subsequent data would not necessarily be reflective of long-term performance of a stand-alone PSVE system.

Table 4.2: Results from Full-Scale Application of Passive Soil Vapor Extraction at the MCB Site, SRS, SC.

Site Name	***MCB***
Location	Savannah River Site, Aiken, SC
Type of Device Utilized	Baroball™
No. of Wells	25
No. of Wells per acre	~ 0.9 (estimated)
Zone of Capture	~ 120 ft (assumed based on well spacing)
Screened Interval	Selected intervals from 0 to 110 ft bgs
Average Flow Rate	2 to 4 cfm
Pore Volumes Removed During Operating Period	Not reported
Starting Vapor-Phase Concentration	37 ppmv TCE; (Average of 19 selected wells)
Ending Vapor-Phase Concentration	13 ppmv TCE; (Average of 19 selected wells after 1.1 yr of operation)
Mass Transfer Rate (/ well)	0.001 to 0.006 yr^{-1} TCE
Mass Removed (per well)	Not reported
Mass Removed (cumulative)	45 lb of total VOCs for first 1.1 yr
Cost	$779 to $1560 per kg removed for first 1.1 yr $469 to $939 per kg removed over 10 yrs

Table 4.3: Results from Full-Scale Application of Passive Soil Vapor Extraction at the MAPSL Site, SRS, SC.

Site Name	***MAPSL***	
Location	Savannah River Site, Aiken, SC	
Type of Device Utilized	Baroball™	MicroBlower
No. of Wells	8	2
No. of Wells per acre	0.3 (estimated)	0.8 (estimated)
Zone of Capture	16 to 26 ft (using 1 yr of flow event data); 9 to 39 ft (using continuous average flow rate)	Not Reported
Screened Interval	85 ft (25 to 110 ft bgs)	10 ft (30 to 40 ft bgs)
Average Flow Rate	2.6 to 7.5 cfm (maximum of 76 cfm)	2 cfm (Data from 1 well)
Pore Volumes Removed During Operating Period	Not reported	Not reported
Starting Vapor-Phase Concentration	~ 45 ppmv PCE ~ 5 ppmv TCE (Average of 5 wells at peak following switch to PSVE system)	250 ppmv PCE 300 ppmv TCE (Data from 1 well)
Ending Vapor-Phase Concentration	~15 ppmv PCE < 2 ppmv TCE (Average of 5 wells following 4.5 yr of operation)	60 ppmv PCE 40 ppmv TCE (Data from 1 well)
Mass Transfer/Removal Rate (per well)	0.03 kg/day PCE; 0.03 kg/day TCE; (Average of 2 wells)	0.06 kg/day PCE; 0.03 kg/day TCE; (Average of 2 wells)
Mass Removed (per well)	6.9 to 144 kg of PCE; 1.5 to 7.7 kg of TCE	37 kg of PCE; 21 kg of TCE
Mass Removed (cumulative)	307 kg of PCE; 29 kg of TCE	Not reported
Cost	Not reported	Not reported

Table 4.4: Results from Full-Scale Application of Passive Soil Vapor Extraction at Four Sites in Denmark.

Site Names	***(1) Møllevej 12, Askov; (2) Nygade 37, Fakse; (3) Prins Valdemars Alle 14, Allerød; (4) Amtsvej 2-4, Allerød***
Location	Counties of Sotrtrøm, Frederiksborg, and Ribe in Denmark
Type of Device Utilized	One-way valve for flow control, coupled with granular activated carbon treatment of off-gases
No. of Wells	Varies, typically 5 to 6 per site
No. of Wells per acre	Varies
Zone of Capture	3 to 13 ft average; 10 to 33 ft maximum
Screened Interval	Varies, but typically across entire unsaturated interval to approx. 60 ft bgs
Average Flow Rate	0.1 to 0.6 cfm
Pore Volumes Removed During Operating Period	25 to 100 during 2 yr operating period
Starting Vapor-Phase Concentration	100 to 300 mg/m^3 PCE (Average)
Ending Vapor-Phase Concentration	30 to 120 mg/m^3 PCE (Average of wells after up to 2 yr of operation)
Mass Removal Rate (per well)	0.1 to 1.0 kg/yr PCE
Mass Removed (per well)	Not reported
Mass Removed (cumulative)	(1) 2 to 3 kg; (2) 5 kg; (3) 8 kg; (4) 50 to 60 kg
Cost	~ $35,000 to $45,000 for typical site with 5 to 6 wells (converted from Danish Krone; excluding VAT)

5.0 KEY CONSIDERATIONS DURING SELECTION OF A PSVE TECHNOLOGY

From a regulatory standpoint, selection of a passive strategy for a site can require more complex and expensive site characterization activities than selection of an active technology. As with other emerging technologies, collaboration between the site remediation team, regulators and stakeholders is key to implementation of pilot studies.

Existing guidance on the selection of passive technologies, such as MNA, advocate a 'converging *lines of evidence*' approach to demonstrate the capability of a passive technology to meet clean-up goals at a site. Based on these converging lines of evidence, passive technologies would most likely receive regulatory approval only if the groundwater plume is stable or shrinking and if the historical data indicates a general decreasing trend in the VOC concentrations over time. At sites where plume conditions indicate that the natural attenuation is occurring at a rate equal to or greater than the mass loading, implementation of a passive source technology could hasten remediation. Thus, to demonstrate the efficacy of a PSVE strategy, site characterization activities would have to include an evaluation of the general site conditions, vadose zone hydrology, source geometry and architecture, groundwater flow conditions, plume behavior, physical and chemical characteristics of the contaminant and contaminant concentrations. At some sites, the use of simple analytical or complex numerical modeling might also be necessary to support the selection of the strategy. Guidance documents such as MNA OSWER directive (1999) provide useful tools to evaluate concentration trends as well as plume stability. See Site Example 3 (grey box) for one method that was used to demonstrate the suitability of a PSVE strategy at the M-Area Abandoned Process Sewer Line (MAPSL) site, SRS, SC.

SITE EXAMPLE 3: CRITERION FOR SELECTION OF PSVE AT THE MAPSL SITE, SAVANNAH, SC

Essentially, an SVE technology is protective of the groundwater only if it is capable of inducing an advective flux of VOCs towards the vent well (V_p) at a rate that exceeds the rate of downward diffusion flux towards the groundwater (V_d).

At the MAPSL site, depth discrete gas concentration data collected from three SVE wells were fitted with an analytical solution of the Ficks' Second Law of Diffusion in order to obtain an estimate of the diffusion flux.

The pore gas velocity or advective flux of VOCs was calculated based on estimates of soil vapor extraction rates, soil porosity, depth of the screened interval and the zone of capture around each extraction well.

Results: Results indicated that the pore gas velocities ranged 10^{-3} and 10^{-4} cm/s at a distance of 10 and 100 ft from the extraction well. Diffusion rates ranged between $2x10^{-6}$ to $8x10^{-6}$ cm/s. These results were comparable to those obtained from robust numerical modeling. Since the $V_p > V_d$, PSVE is a suitable strategy for cleaning up the site.

5.1 Decision Framework for Selection of PSVE Technologies

In the absence of a technology specific decision framework and process documentation, it may still prove difficult to reliably demonstrate to a regulator or a stakeholder that PSVE is sufficient to meet some or all MNA requirements within an acceptable timeframe.

Recently, the ITRC (2008) published a document titled “Enhanced Attenuation: Chlorinated Organics” that includes and explains a decision framework to assess the attenuation capacity of a chlorinated solvent site. The enhanced attenuation strategy relies on an evaluation of the contaminant mass balance to help identify and quantify attenuation processes occurring at the site. The basic premise of EA is that for some sites, source mass flux reductions due to natural attenuation processes may not be sufficient to meet regulatory criteria, causing MNA alone to be an unacceptable treatment option. However, implementation of a suitable technology or a combination of technologies could reduce the source mass flux and/or increase the rate of natural attenuation to an extent that ensures that the site meets MNA requirements. Thus, a site-specific contaminant mass balance could be the basis for determining which remedial technologies are capable of bridging the gap between current site conditions and MNA requirements at the site.

A typical EA assessment entails

- An evaluation of the degree of enhancement in the rate of source flux reductions/natural attenuation that would be needed to create conditions suitable for an MNA application (e.g., a stable or shrinking plume), and;

- Identification of the class of technologies that would most effectively meet site objectives in a timely fashion. Source strength reduction technologies such as SVE, source excavation and infiltration barriers reduce source mass and/or reduce mass flux from the source zone. Attenuation capacity enhancement technologies such as permeable reactive barriers and bioremediation increase the contaminant attenuation rate by promoting abiotic or biological transformation within the plume.

For ease of use, the decision process is presented in flowchart format (Figure 5.1) and is intended to be an iterative process for a smooth, efficient and defensible transition to MNA.

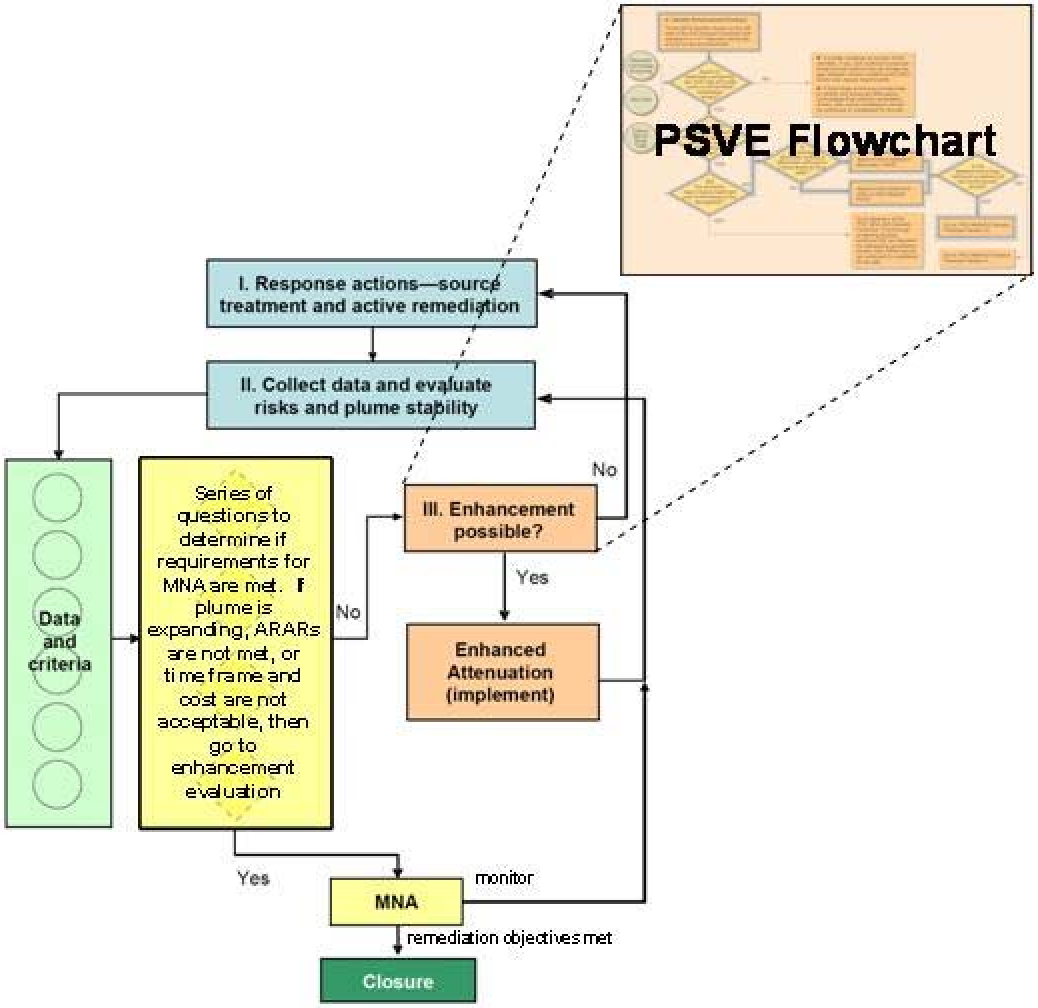


Figure 5.1: Structure of the ITRC EA Decision Flowchart and How the PSVE Flowchart Dovetails into the Process

5.1.2 Decision Process for Selection of PSVE

The ITRC document is a guide to building a strong technically defensible basis for selecting technologies that can accelerate the transition from an active technology to MNA, however, it does not provide any guidance on how to select appropriate technologies. The PSVE decision flowchart (Figure 5.2) was developed to provide decision-makers with a systematic approach to demonstrate the appropriateness of selecting PSVE technologies for chlorinated solvent sites. It is intended to be used in conjunction with the EA flowchart and like the EA process, is intended to be an iterative process that should be repeated during the remedy selection and performance monitoring until MNA or site closure requirements have been achieved.

The PSVE decision process involves the following sequence of five steps:

1. *Identify site conditions that drive the need for an enhancement technology*: This step provides the link to Section iii of the EA flowchart and encourages the user to identify site conditions that make MNA an unacceptable option.

2. *Evaluate whether SVE technologies are suitable for the site*: This step is similar to a conventional remediation technology screening process and helps evaluate whether site conditions or technology limitations preclude the use of SVE.

3. *Determine whether passive SVE technologies can adequately address enhancement drivers*: This step directs users to pilot study data collection and analysis methods that could be used to assess PSVE suitability at the site.

4. *Identify which passive SVE technology is more suitable for the site - barometric pumping or assisted PSVE*: This step helps narrow down the choice of PSVE technologies based on operational differences between the two technologies.

5. *Add selected PSVE technology to remedial configuration and continue evaluating other technologies until all enhancement drivers are eliminated*: This step allows the user to continue evaluating other technologies that could accelerate remedial progress at the site.

The following sections describe the PSVE decision process in more details.

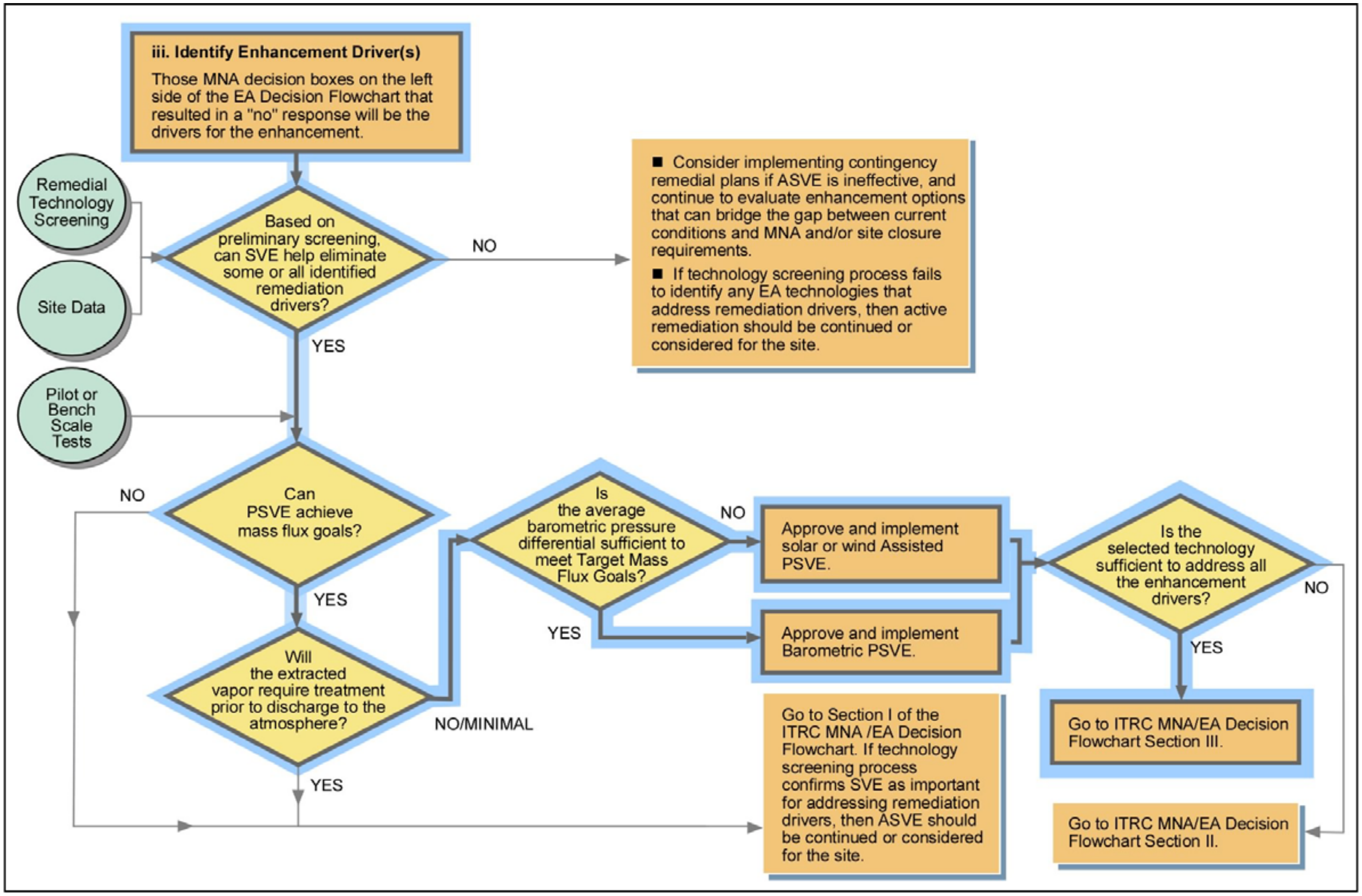


Figure 5.2: Decision Flow Chart for Selection of a PSVE Strategy at a Typical Chlorinated Solvent Site.

5.1.2.1 Identify Site Conditions that Drive the Need for an Enhancement Option

There are five site conditions that are necessary for the selection of MNA at a site. Failure to demonstrate the presence of any one of these conditions precludes the selection of MNA and necessitates selection and implementation of an enhancement technology that can mitigate the failed criteria. The failed criterion thus becomes the driver for an enhancement option, i.e., the “enhancement driver” for the site. Users of the ITRC EA flowchart should have already completed this step before entering the PSVE decision process. However, for the purposes of continuity, the five questions that help evaluate the suitability of selecting MNA at a site are:

1. *Are the current risks acceptable or do current conditions pose an unacceptable risk to a receptor that could be mitigated by implementation of other remediation technologies*?

2. *Is the plume stable or shrinking*?

3. *Are conditions sustainable?*

4. *Is the remediation timeframe acceptable?*

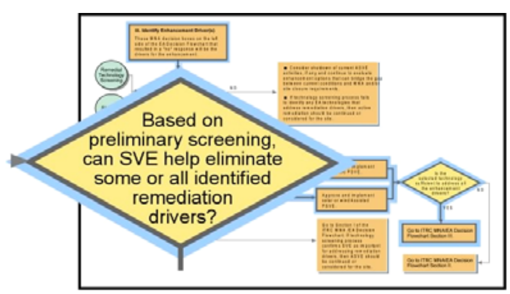
5. *Are the cost-benefits acceptable?*

For more details about how to assess whether MNA is a suitable strategy for a given site or whether an enhancement option will be necessary to accelerate the remedial progress at the site, refer to the Enhanced Attenuation: Chlorinated Organics ITRC Guidance Document (ITRC, 2008).

5.1.2.2 Evaluate Whether SVE Technologies are Suitable for the Site (Preliminary Screening Stage)

For sites where MNA is found to be inadequate, SVE technologies, active or passive, can be an effective means of addressing many of the critical conditions that initially precluded the selection of MNA. However, certain site conditions and technology limitations may preclude the selection of SVE and must be evaluated.

i. *Can SVE Technologies Eliminate One or More Drivers for an Enhancement Option*?



This decision point in the flowchart requires a yes/no response based on existing knowledge of site lithology and hydrogeology, observations made during site reconnaissance surveys and knowledge of the technological strengths and limitations of SVE remedies. This stage is similar to a conventional remedy screening process.

Table 5.1 provides examples of enhancement drivers that can and cannot be addressed by SVE. Typical site-specific parameters necessary to aid the decision process include *radial air permeability of the target zone, contaminant properties, depth to groundwater and the depth and areal extent of the contamination*. If the necessary information regarding these parameters is not available or if the available information suggests that the site-specific conditions are not amenable to remediation by an soil vapor extraction, then the flow chart recommends evaluating technologies other than SVE. For sites with existing ASVE operations, most of this information should already be available. Refer to section 3.2 to determine whether site conditions that preclude selection of an SVE technology exist.

Following this evaluation, a decision-maker might determine that SVE technologies can be employed to eliminate all enhancement drivers at the site. If so, continuing the PSVE decision process would allow for selection of appropriate SVE technologies that would meet all MNA requirements. For sites where SVE is not sufficient to address all of the enhancement options, the flowchart directs the user towards other technologies that can be used in combination with the selected SVE technology to achieve required goals. However, if it is determined that SVE cannot mitigate *any* of the current site conditions that preclude an MNA application, then the flowchart recommends that for sites with active SVE operations, the site manager should immediately implement contingency remedial actions until more appropriate technologies can be identified.

Table 5.1: Potential Benefits or Limitations of Implementing an SVE Strategy based on Site-Specific Drivers for an Enhanced Attenuation Strategy.

Scenarios	*Potential Enhancement Drivers*	*Potential impact of an SVE Strategy*	*Potential Effect on Potential Enhancement Drivers*
1. VOCs are present in the unsaturated zone. Either natural or manmade (cap) present above contaminated zone acts as barrier to upward migration of volatiles.	Unacceptable risk to receptor. Growing plume.	Reduces contaminant mass in the unsaturated zone, thereby reducing the mass flux from the source zone.	May result in sufficient rates of attenuation to counterbalance the loading of contaminants, thus stabilizing and shrinking the plume. With plume shrinkage, receptors of concern may no longer be impacted.
2. VOCs are present in the unsaturated zone. No barrier is present to eliminate upward migration of volatiles, resulting in vapor intrusion issues.	Unacceptable risk to receptor.	Creative placement of wells (possibly horizontal wells underneath structure(s)) will induce vapor transport towards vent wells.	Alternative pathway for VOC removal will minimize, if not negate, risk to receptors.
3. VOCs are present in saturated zone only.	All drivers.	SVE, active or passive, cannot influence dissolved source mass or DNAPL	No impact.
4. VOCs are present in both unsaturated and saturated zones. Natural electron donor supply inadequate for long-term sustainability of biodegradation. Plume presently stable or shrinking.	Sustainability	Reduce the contaminant mass in the unsaturated zone. This will decrease future electron donor demand in the saturated zone.	The decrease in electron donor demand may be sufficient to enable the biodegradation mechanisms to sustain the degradation of the contaminants until remedial goals are reached.
5. If not addressed, the residual VOCs in the unsaturated zone will result in a contaminant plume that will remain above MCLs for a timeframe deemed unsuitable by the responsible parties.	Remediation timeframe is unacceptable.	Reduces loading to the saturated zone. Little impact to leading edge of plume. Impact is to the trailing edge of plume.	Decrease life of plume. May be sufficient to be considered an acceptable timeframe.

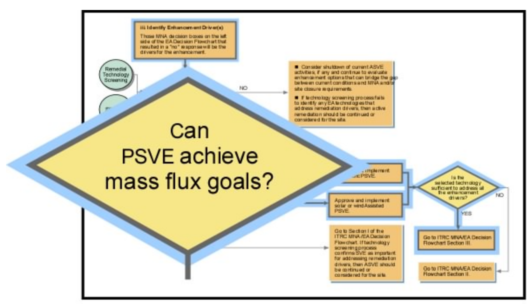
5.1.2.3 Determine Whether Passive SVE Technologies can Address Enhancement Drivers Adequately

The following decision points in the flow chart help identify whether a passive SVE technology could meet remediation criteria within an acceptable timeframe. The following data from pilot SVE tests will help to accurately answer these questions:

- Residual mass in the source zone (obtained from rebound tests)
- Contaminant mass transfer rates (obtained from rebound tests)
- Depth-discrete VOC concentration data
- VOC concentration trends over time (obtained from periodic monitoring during constant-rate vacuum tests)
- Zone of capture or radius of influence for individual extraction wells (obtained from constant rate vacuum tests)
- Preliminary estimates of the remediation timeframe (obtained from constant rate vacuum tests)

For sites with existing SVE operations, most of this data should already be available. For more details about performing pilot studies, refer to the USACE SVE design guidelines (2002).

i. Can PSVE Achieve Mass Flux Goals?



This decision point requires a yes/no response based on a comparison of the target mass flux goal that is protective of the groundwater and the actual mass flux achievable by a PSVE technology at the site (predicted based on pilot studies).

Site Example 2 (grey box) provides one method that was used at the MAPSL site to estimate the target mass flux goals. Appendix A provides rules of thumb (ROT) for predicting the mass flux achievable at a site based on measured soil gas contaminant concentration and estimated values for vertical and radial permeability for the site.

ii. Will the Extracted Vapor Require Treatment Prior to Discharge to the Atmosphere?

Ex-situ treatment of off-gases can be an energy-intensive process that may off-set any cost-benefits derived from implementing a passive remediation technology. There will be cases where vapor treatment via granular activated carbon (GAC) canisters may be installed cheaply. For the remaining sites, ASVE may be more appropriate. However, once off-gas concentrations decrease to acceptable levels, PSVEs might offer more advantages as a polishing technology.

This decision point requires a yes/no response based on the comparison of actual and predicted mass removal rates to Applicable or Relevant and Appropriate Requirements (ARARs).

If the response to both the decision points is “No”, then PSVE might be a suitable option for the site. However, if the response to either question is “Yes”, PSVEs may not be suitable for the site. The user should instead consider ASVEs as an option to accelerate remediation. If ASVEs are already operating at the site, the user might consider continuing the ASVE program or identifying other alternatives that might help achieve MNA requirements in a more timely and cost-effective manner. For users interested in identifying alternatives, the flowchart directs users to Section iii of the EA flowchart. This gives the user an opportunity to re-evaluate other methods of mitigating the failed criteria for MNA.

5.1.2.4 Identify Which Passive SVE Technology is More Suitable for the Site - Barometric Pumping or Assisted PSVE

At this stage in the flowchart, responses to earlier decision points indicate that PSVEs might be a suitable addition to the remedial strategy for the site. However, in order to select the appropriate PSVE technology, it is necessary to evaluate whether target extraction rates can be met under barometric conditions at the site. Figure 5.3 compares estimated soil gas flow generated during a barometric application versus that generated using a MicroBlower at an SRS site.

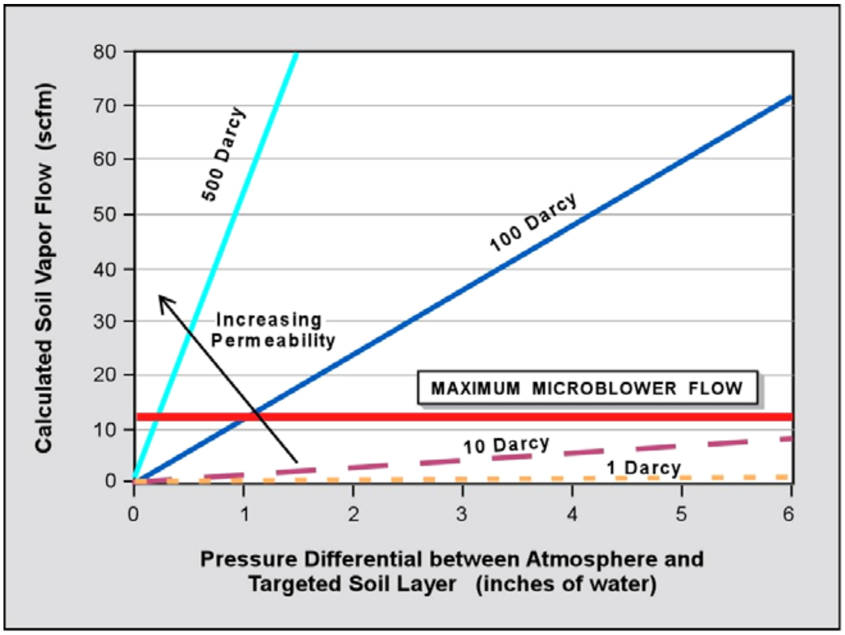
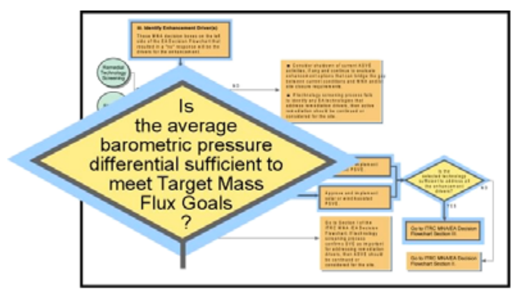


Figure 5.3: Comparison of Soil Gas Flow generated during a Barometric Application versus that generated using a MicroBlower at SRS, SC.

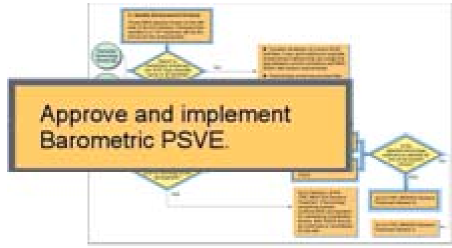
While barometric applications can generate higher instantaneous flows during outflow conditions, the intermittent nature of the application may make selection of barometric pumping unfeasible.

i. Is the Average Pressure Differential between Atmospheric and Target Subsurface Zone Sufficient to Meet Target Mass Flux Goals?



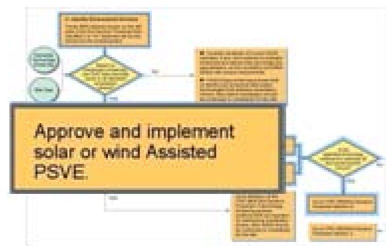
This decision point requires a yes/no response based on the target mass flux goals determined earlier and the average mass flux that can be achieved using barometric pumping. In addition to the data requirements outlined in the previous section, the pilot study for evaluation of barometric pumping should be designed to collect long-term surface and subsurface pressure data as well as barometric soil gas flow rates.

Methods for collection of this data are described in Section 2.4. See Appendix A for predicted values for soil gas flow rate and contaminant mass flux based on the physical properties of the overlying soil and the affected soil layers.



If the pressure differential at the site is sufficient to achieve the target extraction rates (response to question is "Yes"), then barometric pumping might be a suitable option at the site. As with all strategies, long-term performance monitoring will be necessary to ensure that remedial progress is occurring in a timely and sustainable fashion.

If results from performance monitoring indicate poor performance by the barometric pumping wells, then contingency plans described in the ITRC EACO flowchart will have to be activated to ensure continued remedial progress at the site.

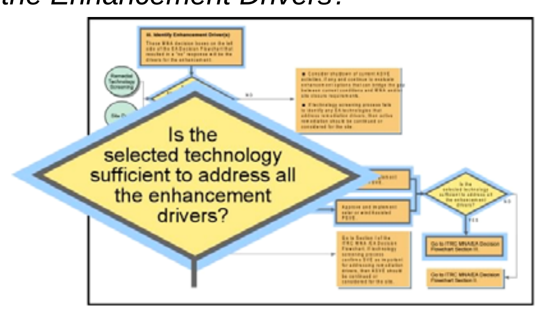


If the pressure differential at the site is not sufficient to produce the desirable mass extraction rates (response to question is "No"), then pumping using a MicroBlower might be a suitable option. The selection of an energy source, solar or wind, for the MicroBlower will depend on site-specific conditions. As described in Section 4, both solar-powered and wind-powered PSVE systems have been installed at Department of Energy facilities with great success. As with the barometric pumping system, it will be important to monitor the system over the long-term to ensure that the system is performing at the levels necessary to meet all MNA or site closure requirements within an acceptable timeframe.

5.1.2.5 Add Selected PSVE Technology to Remedial Configuration and Continue Evaluating Other Technologies until All Enhancement Drivers are Eliminated

If PSVE is incapable of eliminating all of the enhancement drivers, then it is important to continue evaluating other complementary or compatible technologies that could help meet MNA requirements.

i. Is the Technology Sufficient to Address All the Enhancement Drivers?



This decision point requires a yes/no response based on the original list of enhancement drivers identified for the site. If the response is a "Yes", then the flowchart directs the user to approve and implement the selected PSVE technology. Following this, the flowchart directs the user to Section ii of the EA flowchart so that the site conditions can be re-evaluated to check if they meet MNA requirements.

However, if the response is a “No”, then the flowchart would direct the user back to the EA flowchart where they would then evaluate the new mass balance that incorporates the contributions of the selected PSVE in order to identify the next enhancement option for the site.

If for some reason, at this stage, implementation of PSVE technologies becomes unlikely either due to concerns raised by the regulatory authority or by other stakeholders, then the PSVE flowchart would direct the user to Section III of the EA flowchart where they can screen other potential technologies that might be appropriate and acceptable for their site.

5.1.3 Flowchart Summary

The PSVE flowchart provides a process through which decision-makers can determine whether PSVE systems can help transition a site from an active remedial strategy to an MNA strategy. The decision process is iterative in nature and is intended to be used in conjunction with the EA decision process (ITRC, 2008). Like the EA decision process, the PSVE decision process acknowledges that PSVE is only one of many technologies that can be used to eliminate enhancement drivers at the site and encourages decision-makers to develop a combination of remedial technologies to address site conditions that would otherwise preclude the use of MNA at the site.

6.0 OCCUPATIONAL SAFETY AND HEALTH

6.1 Technology-Specific Health and Safety Risks

- There are no technology-specific health and safety risks associated with either the one-way passive valves used for barometric pumping or the blowers used for assisted PSVE applications.
- The risk profile for PSVE technologies is generally safer than ASVE due to the low or no energy usage and lower mass flux through the system.

6.2 Worker Safety

- As is the case with implementation of any remediation technology, the site workers should be OSHA-certified.
- A Health and Safety plan that describes chemical risks associated with working at a particular site will be necessary.
- However, overall, implementation of a PSVE strategy does not pose any additional risks to a worker other than the standard risks associated with construction operations and those associated with working at a contaminated site.

6.3 Community Safety

- As long as the discharge of extracted soil vapor meets appropriate regulatory action levels and or site specific target levels, implementation of a PSVE strategy should not pose any community safety issues associated with the installation or operation of either PSVE technology.

7.0 REGULATORY AND POLICY ISSUES

7.1 Regulatory Considerations

The decision process for selection of PSVE technology is a novel method that is currently gaining acceptance within the regulatory circles. An ITRC survey of regulators in 34 states in the contiguous United States indicated that a majority of the respondents support the development of technical procedures and decision processes based on an evaluation of contaminant mass balance (ITRC, 2008). Nevertheless, it is crucial that communication with regulators be established early-on and regularly as part of the decision process when novel technologies such as PSVEs are being considered.

- At Federal facilities, a National Environmental Policy Act (NEPA) review is required.

- Comprehensive Environmental Recovery, Compensation, and Liability Act (CERCLA) or Resource Conservation and Recovery Act (RCRA) corrective action permitting may be required.

7.2 Risks, Benefits, and Community Reaction

- There are no unusual or significant safety concerns associated with PSVE implementations. However, as vapor intrusion becomes more recognized as a potential receptor pathway, the use of this technology may garner some concern from communities and this should be considered when developing strategies for communicating risk to impacted communities.

- Assuming that all ARARs are adhered to during the course of the remediation, no impacts to receptors are anticipated as a result of implementing a PSVE technology.

7.3 Environmental Impact

- Compared to ASVE technologies, PSVEs may require additional well installation in order to provide adequate coverage of the source area. Although PSVE wells can often be installed using direct push technologies which generate very little waste, it is possible that a greater amount of drill cuttings and drill fluid will be generated as a result of a passive strategy. However, PSVE operations would result in a reduced carbon footprint and energy usage as compared to ASVE operations.

- Assuming that all ARARs are strictly adhered to during the course of the remediation, impacts to the ambient air should be minimal.

- As long as the PSVE meets all performance metrics, no impacts to the nearby surface water bodies or groundwater is anticipated.

7.4 Socioeconomic Impacts and Community Perception

- PSVEs have minimal economic or labor force impact

- The general public has limited familiarity with the PSVE technology; however, if remedy selection occurs within the framework of the decision process described in Section 4, selection of PSVEs should not face much resistance.

- Communities are generally receptive to technologies that use renewable or natural energy to accomplish their task.

8.0 COST FOR USE OF PSVE TECHNOLOGIES WITHIN AN EA STRATEGY

As with all technologies, a rational and technically-based cost evaluation requires quantification of the various drivers and counterbalanced factors to determine the relative merit of each alternative. The factors that influence costs for PSVE relate to the vadose zone, physical and chemical properties, the infrastructure required to achieve remediation goals (i.e., the number, spacing and design of extraction wells), and the projected costs for operating and maintenance (O&M) and monitoring. Rather than providing a traditional detailed cost evaluation in this summary report (see Cummings and Booth, 1996 for an example), typical site-specific factors that may impact the cost of implementing PSVE are presented and discussed. The evaluation is from the perspective of a typical site owner who has an ASVE system in place and plans to transition to a PSVE system. This is expected to be the typical scenario for considering PSVE within an EA strategy. In this case, the desire will be to use existing ASVE wells.

8.1 Cost Drivers

The fundamental technical viability of PSVE depends on vadose conditions and installation requirements at an appropriate site. For example, a site with a thin vadose zone that does not have lithologic or pressure isolation of the targeted depth interval is not suited to barometric pumping. When comparing PSVE to alternatives such as ASVE, the equipment and O&M costs tend to be significantly lower, but the lower flow rates that are achievable with PSVE may require closer well spacing and a larger number of wells.

The primary considerations in using existing wells include the following:

- Well spacing must be sufficient to provide needed PSVE coverage and contaminant removal rate.

- Screened depth intervals must target appropriate zones to maximize efficiency.

If the existing extraction well network is insufficient to adequately meet remedial goals after a transition to PSVE, then the capital costs associated with installing additional extraction wells must be factored into the overall cost evaluation. The costs of drilling new wells are site-specific, but the most important factor is the depth interval being targeted for PSVE. At sites with shallow vadose zones, direct push methods can be used to provide rapid drilling rates and a high degree of flexibility, such that installation costs may be $1,000 to $2,000 per well or less. At sites with deep vadose zones where rotary drilling or other conventional deep-drilling techniques are required, installation of a single well could take several days to a week or more. At these sites, installation costs can easily exceed $2,000 per well and may approach up to $10,000 per well at particularly complex sites. As a consequence, these costs may rule out PSVE if a large number of wells must be installed to meet performance objectives (e.g., complete coverage of source area).

The wellhead equipment costs are typically low for PSVE compared to active SVE. The devices used for barometric pumping (e.g., Baroball™) can generally be purchased or fabricated for less than $50. As an example of the cost of typical equipment for assisted PSVE applications, the 24 V MicroBlower system can be fabricated from materials that range between $200 and $300, most of which is related to the blower. While there are other costs associated with these systems, it is clear that for the average site, the costs of the wellhead equipment will be a fraction of the well installations.

At sites where assisted PSVE is being considered, one decision is whether to use traditional power sources or renewable sources to power the small vacuum blowers that are part of these systems. Renewable or “green” technologies, such as wind or solar power, can be supplemented with external power sources or batteries to provide backup power when necessary. Factors affecting costs include:

- ***Availability of existing traditional power sources.*** Sites that are located far from existing power grids may be able to tap renewable power sources more cost-effectively than other alternatives (e.g., generators).

- ***Credits for use of green technologies and/or carbon abatement.*** These can be in the form of direct subsidies or incentives for using renewable power sources, or as a cost savings accrued by preventing greenhouse gas emissions (e.g., emissions credits, offsets, carbon tax avoidance).

- ***Reliability of green technologies to maintain performance of the treatment system.*** At some sites, the use of wind or solar may be impractical. An extreme example would in areas, where there is minimal sunlight for extended periods in the winter, meaning that the cost-effectiveness of a solar-powered system would be negated by the need for extensive backup power supply. Similarly, site restrictions related to the height of structures may preclude the use of wind power as even small wind turbines installed on towers typically must be at least 30 ft higher than surrounding structures.

Green sources have little or no power costs associated with their use, assuming that they are installed with no traditional power backup. However, there are costs associated with the installation, operation, maintenance, and replacement of these assisted PSVE systems. The capital costs typically range from $4 to $7 per watt for a single solar panel of approximately 150 to 200 W (max power) and energy storage system (batteries) that are sufficient to operate a small vacuum blower. Capital costs for a wind-power assisted PSVE system include $3,000 to $20,000 for a single wind turbine (1 kW to 5 kW) that can typically run a full suite of small vacuum blowers at site, and energy storage system (batteries) to provide backup power ($200 to $300 per well). The exact sizing (and thus costs) of these units will be dependent on the ratio of time the system is generating energy from solar or wind to the time it relies on back-up (battery) power each day.

Barometric SVE systems have no power costs and thus represent a potential for significant reductions in costs over the lifecycle of a typical project (years to decades).

A summary of potential cost drivers for PSVE systems is presented in Table 8.1. When applicable, these are presented in terms of potential cost outlays or potential cost savings relative to ASVE systems. As such, it is intended to provide guidance for evaluating the merits of switching from an ASVE system to a PSVE system at a given site.

Table 8.1: Cost Drivers for Comparing Transition to PSVE System from an Existing ASVE System

Cost Driver	Description	Estimated Cost Range

1) Preliminary technology and site assessment	• Objective is to assess if switch to PSVE will adequately address enhancement drivers
	• Implement treatability testing and/or pilot testing to the extent necessary
	  • Assessment can include vacuum measurements, mass removal rates, rebound tests
	  • Up to several months of monitoring
	• Utilize existing ASVE well(s) and install passive device during testing
		$2K - $10K per well
		
		(capital costs including equipment, labor, and analytical)

2) Above-ground treatment requirements	• Concentration of gas from PSVE extraction wells generally should not exceed permissible air discharge limits • Typical above-ground treatment technologies (catalytic/thermal oxidation and activated carbon adsorption) could have high O&M costs. Depending on the loading rate, granular activated carbon (GAC) may be installed cheaply. • If above-ground treatment is required, then cost may eliminate PSVE as an cost-effective option (particularly at large sites) • Typical option for above-ground treatment for PSVE wells is small activated carbon unit	Costs for Small ASVE sites (10 to 200 scfm): Activated carbon $0.2K to $10K annually; oxidation $10 to $100K annually Large ASVE sites (>1,000 scfm): Activated carbon > $50K annually; oxidation $100 to $300 K annually (plus capital costs)
3) Installation of new PSVE wells	• Additional wells may be required depending on results of preliminary testing • PSVE wells have lower airflow rates and zones of influence, so existing SVE well configuration may be inadequate • PSVE is most effective in vadose zones where presence of isolated intervals contribute to significant barometric pressure differentials, but this may make for costly drilling (time-consuming; direct-push impratical)	$1K to $2K per well for shallow sites where direct-push used to install wells $2 to $10 K per well for deeper sites where conventional drilling used to install wells

Cost Driver	Description	Estimated Cost Range
4) Installation of PSVE devices	• Most existing PSVE devices are simple designs with very low cost • Barometric pumping devices have long lifetimes, with many installations operating continuously without replacement. Baroball™ valves should be checked regularly and changed as needed to ensure proper operation. • Assisted PSVE devices (e.g., MicroBlower) have lifetimes of up to several years. However, certain components should be changed more frequently: motors (every 6 to 12 months) and deep-cycle batteries (as needed).	Barometric Pumping: $10 to $50 per well (example: Baroball™ ~ $13 per well) plus labor (minimal, typically 1-2 days per site) Assisted PSVE: ~ $2 K per well using solar-power as primary and battery as back-up; higher for wind-powered system unless site is large; plus labor (minimal, typically 1-2 days per site)
5) O&M	• Minimal to no energy costs except for certain MicroBlower applications (battery back-up) • Devices require little maintenance or oversight during operation	< $1 K annually per site for routine checks and maintenance
6) Remedial timeframe	• PSVE is unlikely to decrease remedial timeframe relative to ASVE unless a much larger number of wells are installed (increasing capital costs) • Longer remedial timeframe typically has minimal impact on lifecycle costs because O&M for PSVE is low • Protection and/or restoration of resources (e.g., sale of restored property to recoup cleanup expenditures) may influence decisions on accelerating cleanup date	Negligible, unless restoring use of resource is driving cleanup date
7) Sustainability issues	• PSVE is low carbon footprint technology due to minimal energy usage, minimal maintenance, low reliance on fabricated materials and infrastructure, and no requirement for combustion/conversion of contaminant • Cost for carbon emissions is negligible (best captured by lower O&M expenditures) but may be significant if regulatory framework and market forces become drivers	Negligible under current regulatory framework

Cost Driver	Description	Estimated Cost Range

8) Other site characteristics	• Site Location:
	  • poor performance of wind and solar-powered devices (MicroBlower) if local conditions are unfavorable
	  • access to centralized power supply may be limited or not cost-effective
	  • infrastructure at site may limit ability to install additional wells (e.g., urban sites, industrialized or active sites)
	• Existing ASVE system may be difficult or inefficient to convert to PSVE (e.g., intervals that do not isolate target depth interval)
	• Airflow rates: higher rates reduce unit cost ($/lb of contaminant removed) but there is no external control (function of formation and climatological properties)
	• Steady-state concentration of gas from PSVE wells: higher concentrations reduce unit cost ($/lb of contaminant removed) but may necessitate above-ground treatment
		Varies depending on site characteristics

8.2 Site-Specific Scenarios

The following section presents a series of hypothetical sites with specific characteristics that directly influence the cost and viability of switching to PSVE.

8.2.1 Scenario 1: PSVE is Cost-Effective at Site with Existing ASVE System and No Requirement for New Wells

Site Information: At this hypothetical site, the performance of the existing ASVE system (in terms of mass removal rate per well) has begun to decline, and extensive pilot-scale testing ($10,000) has determined that the existing system of 10 extraction wells provides adequate coverage to meet technology requirements and performance objectives for a PSVE system. As such, there are no costs associated with drilling additional wells, and the primary capital costs are associated with installation of Baroball™ valves at each wellhead ($500). It is estimated that the entire PSVE system can be installed in a single day (labor costs of $1,000). The monitoring schedule for the PSVE system is identical to that for the previous ASVE system, but the primary O&M savings occur as a result of eliminating power requirements for the ASVE blowers ($2,000 annually) and all components of the granular activated carbon (GAC) treatment system ($3,000 annually), as well as the associated maintenance of these systems ($1,000 annually).

Table 8.2: Cost Evaluation for Site-Specific Scenario 1.

Key Cost Components	
Pilot test cost	$10,000
Equipment costs for Baroball™ valves	$500 ($50 per well)
Labor cost for installation	$1,000 ($1,000 for 1-day installation period)
TOTAL COST	$11,500
Key Savings Components (relative to ASVE)*	
Power Savings	$2,000 per year
Treatment Savings	$3,000 per year
Other O&M savings	$1,000 per year
TOTAL SAVINGS (excluding costs)	$6,000 per year
TOTAL SAVINGS (including costs)	$34,000 over 10 year operating period

*Discount rate = 3%

Results of Cost-Benefit Evaluation: For this type of idealized site, the switch to PSVE represents a net cost savings within 2 to 3 years and will approach $30,000 to $40,000 in cost savings (in net present value) over the course of a ten-year operating period. Based on these projections, the use of small vacuum blowers could also be chosen to complement the PSVE system since the potential cost savings from the switch from ASVE still exceeds the typical capital costs associated with assisted PSVE ($2,000 per well for solar-powered MicroBlowers installed at 10 wells).

8.2.2 Scenario 2: PSVE May Not be Cost-Effective at Site Where New Wells are Required

Site Information: Preliminary pilot-scale testing ($10,000) demonstrated that a portion of this federal site was not adequately covered by the 10 wells that make up the existing ASVE system. To meet PSVE technology requirements and performance objectives, 5 additional wells will be installed that target the same depth intervals as the existing wells. These wells are to be screened in lithologically-isolated intervals that will increase the effectiveness of PSVE, but because these intervals are relatively deep (40—60 ft bgs and 80—100 ft bgs) and must advance through several difficult intervals, the quote from the subcontractor for drilling these wells is $50,000 (including all mobilization and oversight costs). The primary capital costs are associated with installation of Baroball™ valves at each wellhead ($500), and it is estimated that the entire PSVE system can be installed in a single day (labor costs of $1,000). The monitoring schedule for the PSVE system is identical to that for the previous ASVE system, and the primary O&M savings occur as a result of eliminating power requirements for the ASVE blowers ($2,000 annually), all components of the GAC treatment system ($3,000 annually), and the associated maintenance of these systems ($1,000 annually).

Table 8.3: Cost Evaluation for Site-Specific Scenario 2.

Key Cost Components	
Pilot test cost	$10,000
Drilling cost for installing new PSVE wells	$50,000 ($5,000 per well)
Equipment costs for Baroball™ valves	$500 ($50 per well)
Labor cost for installation	$1,000 ($1,000 for 1-day installation period)
TOTAL COST	$61,500
Key Savings Components (relative to ASVE)*	
Power Savings	$2,000 per year
Treatment Savings	$3,000 per year
Other O&M savings	$1,000 per year
TOTAL SAVINGS (excluding costs)	$6,000 per year
TOTAL SAVINGS (including costs)	$5,000 over 20 year operating period (break even point occurs after 17 years)

*Discount rate = 3%

Results of Cost-Benefit Evaluation: For this type of idealized site, the switch to PSVE will represent a net cost savings only after an extended operating period of 15 to 20 years (based on net present value). Consequently, PSVE may only be cost-effective over a reasonable project lifecycle if the number of new PSVE wells can be decreased to 3 or less (e.g., focusing only on a source area) or if greenhouse gas emissions from the ASVE system become an important cost driver. Alternatively, it may be that the switch from ASVE to a PSVE system does not completely eliminate the need for above-ground treatment of vapors, such that a small GAC treatment unit may have been required for some or all of the PSVE wells. This is not an unrealistic scenario when new extraction wells are installed it is possible that initially "high levels" of contaminant mass are present requiring off-gas treatment. In this case, treatment of PSVE vapors likely would have eliminated PSVE as a cost-effective option for this site.

8.2.3 Scenario 3: PSVE is not Cost-Effective Due to Site-Specific Issues

Site Information: At this larger site, the existing ASVE system is no longer performing in a cost-effective manner, and more economical options are being explored. Annual O&M costs for the ASVE system, including the air stripper for vapor treatment, are typically $5,000 per year. Limited pilot-scale testing ($3,000) demonstrated that barometric pumping could be an effective mechanism for capturing vapors from the low permeability zones in the source area, but that an additional 5 to 10 wells must be installed to provide adequate coverage. A further assessment determined that migration of contaminants to groundwater is no longer occurring in areas down-gradient of the source, such that ASVE wells in these areas (20) will also be converted to PSVE wells (using barometric pumping). The cost associated with drilling these additional wells are projected to be $50,000 due to site constraints, which is difficult for the site manager to justify based on the large capital expenditure and the disruption to site activities caused by drilling. The use of assisted PSVE is proposed because the higher airflows achieved by these low vacuum devices would be sufficient to minimize the need for additional wells. However, because a large number of the existing wells that would be converted to PSVE wells are located in restricted areas with limited access to sunlight (and no wind), these devices would need to rely exclusively on battery power.

Table 8.4: Cost Evaluation for Site-Specific Scenario 3.

Key Cost Components	***Barometric PSVE***	***Assisted PSVE***
Pilot test cost	$3,000	$3,000
Drilling cost for installing new PSVE wells	$50,000 ($5,000 per well)	Not required
Equipment costs for PSVE valves	$500 ($50 per well)	$24,000 ($1200 per well for battery power)
Labor cost for installation	$1,000 ($1,000 per day for 1-day installation period)	$3,000 ($1,000 per day for 3-day installation period)
O&M costs (batteries)	Not required	$15,000 per year
TOTAL COST	$54,500	$30,000 for first year; $15,000 per year in following years
Key Savings Components (relative to ASVE)*		
Power Savings	$2,000 per year	$2,000 per year
Treatment Savings	$2,000 per year	$2,000 per year
Other O&M savings	$1,000 per year	$1,000 per year
TOTAL SAVINGS (excluding costs)	$5,000 per year	$5,000 per year
TOTAL SAVINGS (including costs)	< $1,000 over 20 year operating period, break even point occurs after 19 year operating period)	< $0 over any proposed operating period

*Discount rate = 3%

Results of Cost-Benefit Evaluation: The cost associated with regular change-out of batteries ($500 to $1,000 per well per year), as well as the capital costs associated with the initial installation of the systems ($1,000 to $1,500 per well for 20 wells), precluded their use, and as a consequence, assisted PSVE was eliminated as an option.

9.0 REFERENCES

Christensen, A.G., Nielsen, H.H. and E.V. Fischer. 2003. Passive Ventilation of PCE in Unsaturated Zone. Technical Project Report No. 805 2003. Prepared as part of the Miljøstyrelsens (Danish EPA) Technology Demonstration Program.
http://www2.mst.dk/Udgiv/publikationer/2003/87-7972-610-0/pdf/87-7972-611-9.pdf

ESTCP (Environmental Security Technology Certification Program), 2006. Design Document for Passive Bioventing. Prepared under the ESTCP Program at Department of Defense (DoD), Arlington, Virginia. ESTCP-9715. March 2006.

ITRC (The Interstate Technology & Regulatory Council). 2008. Enhanced Attenuation: Chlorinated Organics. Technical and Regulatory Guidance prepared by EACO-1, Enhanced Attenuation: Chlorinated Organics Team. Washington, D.C. April 2008. http://www.itrcweb.org/Documents/EACO-1.pdf

ITSER (Innovative Technology Summary Report). 2000. Barometrically Enhanced Remediation Technology (BERT™). Prepared for Office of Science and Technology, US Department of Energy (DOE). DOE/EM-0516. March 2000.

McGuire, T.M., Newell, C.J., Looney, B.B., Vangelas, K.M., and C.H. Sink. 2004. Historical analysis of monitored natural attenuation: A survey of 191 chlorinated solvent sites and 45 solvent plumes. *Remediation*, Winter 2004, Pg 99-112

McGuire, T. M., McDade, J.M., and C.J. Newell. 2005. Performance of DNAPL Source Depletion Technologies at 59 Chlorinated Solvent-Impacted Sites. *Groundwater Monitoring and Remediation*, Vol. 26, No. 1, Pg 73 – 84.

Neeper, D. A. 2002. Investigation of the Vadose Zone using Barometric Pressure Cycles. *Journal of Contaminant Hydrology*, No. 54, Pg 59-80.

O'Brian, 2001 Passive soil vapor extraction: a low cost complement to conventional active-extraction method. Technology Highlight Archive. As referenced in Jennings, A. and P. Patil. 2002. Feasibility Modeling of Passive Soil Vapor Extraction. *Journal of Environmental Engineering and Science*. Vol. 1, Pg 157-172.

Riha, B. D. and J. Rossabi. 1997. Miscellaneous Chemical Basin Treatability Study: An Analysis of Passive Soil Vapor Extraction Wells (PSVE). Washington Savannah River Company. WSRC-TR-97-00405. December 1997.

Riha, B. D., Rossabi, J., and W. K. Hyde. 1999. Metallurgical Laboratory (MetLab) Treatability Study: An Analysis of Passive Soil Vapor Extraction Wells (PSVE) FY 1999 Update. Washington Savannah River Company. WSRC-TR-99-00378. October 1999.

Riha, B. D, Jackson, D. G., Hyde, W. K., Looney, B. B. and J. Rossabi. 2001. Vadose Zone Remediation Assessment: M-Area Process Sewer Soil Vapor Extraction Units 782-5M, 782-7M and 782-8M. Washington Savannah River Company. WSRC-TR-2001-00077. February 2001.

Riha, B. D. 2005a. Vadose Zone VOC Mass Transfer Testing at the SRS Miscellaneous Chemical Basin. Washington Savannah River Company. WSRC-TR-2005-00266. October 2005.

Riha, B. D. 2005b. Passive Soil Vapor Extraction (PSVE) for VOC Remediation at the Metallurgical Laboratory (MetLab), June 2005 Progress Report. Washington Savannah River Company. WSRC- TR- 2005-00268. June 2005.

Riha, B. D. 2005c. Performance Testing of Passive Soil Vapor Extraction (PSVE) along the M-Area Abandoned Process Sewer Line (MAPSL). Washington Savannah River Company. WSRC-TR-2004-00143. June 2005.

Rohay, V.J., Rossabi, J., Looney, B., Cameron, R., and B. Peters. 1993. Well Venting and Application of Passive Soil Vapor Extraction at Hanford and Savannah River. Westinghouse Hanford Company. WHC-SA-2064-FP. September 1993.

Rohay, V.J., Cameron, R. J., Peters, B. B., Rossabi, J., Riha, B., and W. Downs. 1997. Passive Soil Vapor Extraction. Prepared for the Office of Environmental Restoration, US Department of Energy (DOE). BHI-01089. August 1997.

Rossabi, J. 1999. The Influence of Atmospheric Pressure Variations on Subsurface Soil Gas and the Implications for Environmental Characterization and Remediation, Ph.D. Dissertation, Clemson University, Alabama.

Rossabi J., and R. W. Falta. 2002. Analytical Solutions for Subsurface Gas Flow to a Well Induced by Surface Pressure Fluctuations. *Groundwater*, Vol. 40, No. 1, Pg 67 - 75.

Riha, B.D. and T. Whiteside. 2008. Transition from Active to Enhanced Attenuation (EA) using Passive Soil Vapor Extraction. Proceedings of the Sixth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California. May 19-22, 2008.

USACE. 2002. Engineering and Design - Soil Vapor Extraction and Bioventing. Prepared by US Army Corp of Engineers. EM 1110-1-4001. Available at http://140.194.76.129/publications/eng-manuals/em1110-1-4001/toc.htm

APPENDIX A:
PREDICTING MASS FLUX FOR A BAROMETRIC PUMPING APPLICATION BASED ON SITE SPECIFIC PARAMETERS

In the absence of long-term pressure data, Rossabi and Falta (2002) provide a simple analytical solution for predicting soil gas flow rates based on the atmospheric pressure, depth of the target zone and the vertical permeability of the overlying strata. Under typical conditions, data from a short-term pilot study (~ 2 weeks) should be sufficient to calibrate the model. Once calibrated, future soil gas flow rates from the extraction wells can be predicted based on pressure data from local meteorological stations. Using Figures A.1 and A.2, a user can predict typical values for soil gas flow rates based on estimated or known radial permeability of the target soil layer and vertical permeability of soils overlying the impacted soils. Figure A.3 allow a user to make preliminary estimates of the contaminant mass flux based on measured soil gas VOC concentrations and predicted soil gas flow rates.

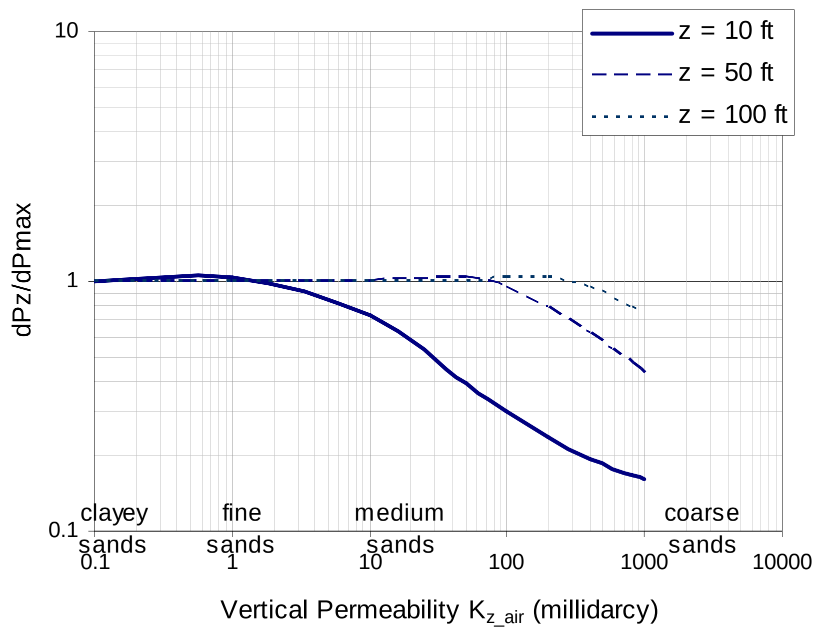


Figure A.1: Predicted values for differential pressure between the atmosphere and the screened interval as a function of the height and average permeability of the soil column overlying the screened interval. Values calculated using equations presented in ESTCP, 2006.

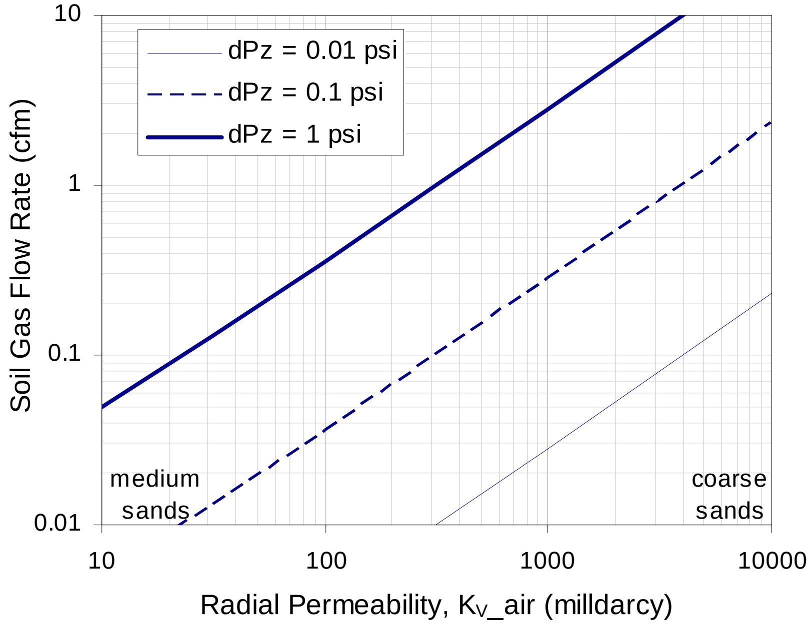


Figure A.2: Predicted value for soil gas flow rates as a function of the differential pressure between the atmosphere and the screened interval and the permeability of the screened interval. Values calculated using equations presented in Appendix A.2 of ESTCP, 2006 and the following assumed parametric values: well diameter = 2 inches, screen length = 10 ft)

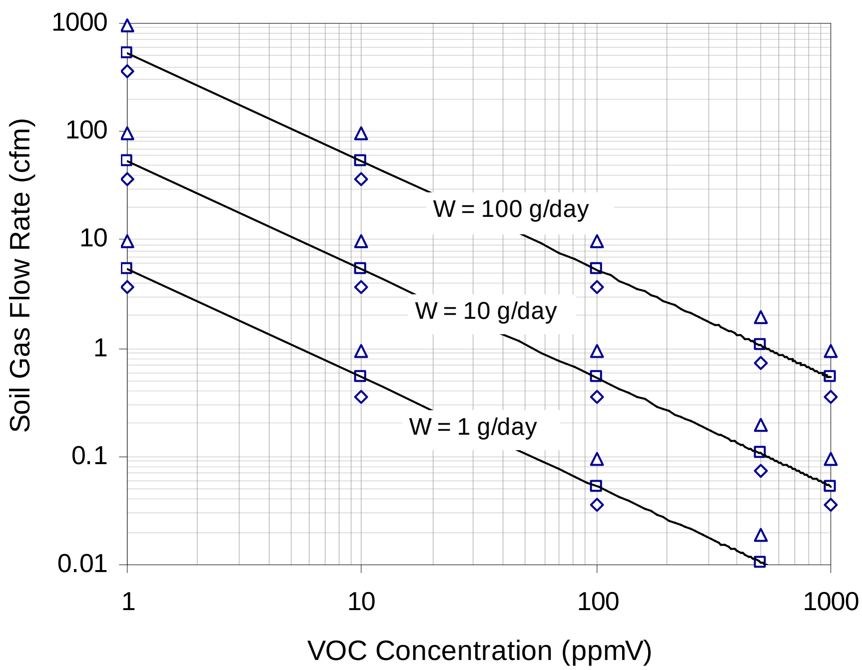


Figure A.3: Contaminant mass flux (W) as a function of the VOC concentration and actual or estimated soil gas flow rates for a PSVE well. ◇ PCE; □ Chlorobenzene; △ Vinyl Chloride.

APPENDIX B: TECHNOLOGY DEMONSTRATION DESIGN, IMPLEMENTATION AND RESULTS

This section presents additional detail and references for the case studies presented in Section 5.

B.1 Metallurgical Laboratory (MetLab)

Information for the site was drawn primarily from the contract report WSRC-TR-2005-00268, entitled *Passive Soil Vapor Extraction (PSVE) for VOC Remediation at the Metallurgical Laboratory (MetLab) June 2005 Progress Report*. The report is publicly-available and can be downloaded at http://www.durhamgeo.com/pdf/Rem-pdf/Other/WSRC-TR-2005-00268%20MetLab.pdf. Additional information was obtained from the authors of the report.

B.1.1 Site Description

- ***Location:*** The Metallurgical Laboratory (MetLab) waste unit is located at the Savannah River Site (SRS), within the A/M areas.
- ***Site History:*** PCE and TCE were the primary solvents used at the site. Historic releases created vadose zone soil impacts and a soil gas plume.
- ***Site Hydrogeology:*** The Metlab unit is underlain by unconsolidated sediments consisting of sands, clayey sands, and sandy clays, as is the entire SRS. The fine-grained intervals of primary interest are between 0 to 15 ft and approximately 60 and 80 ft below ground surface (bgs). The water table is encountered at approximately 140 ft bgs.
- ***Pre-Test Conditions:*** Characterization studies included extensive soil and soil gas sampling that confirmed the presence of a source at the south side of Building 717-A. Soil gas concentrations ranged up to 88.4 ppmv TCE and 121.6 ppmv PCE in this area, with evidence of migration of the gas plume to the north and east.

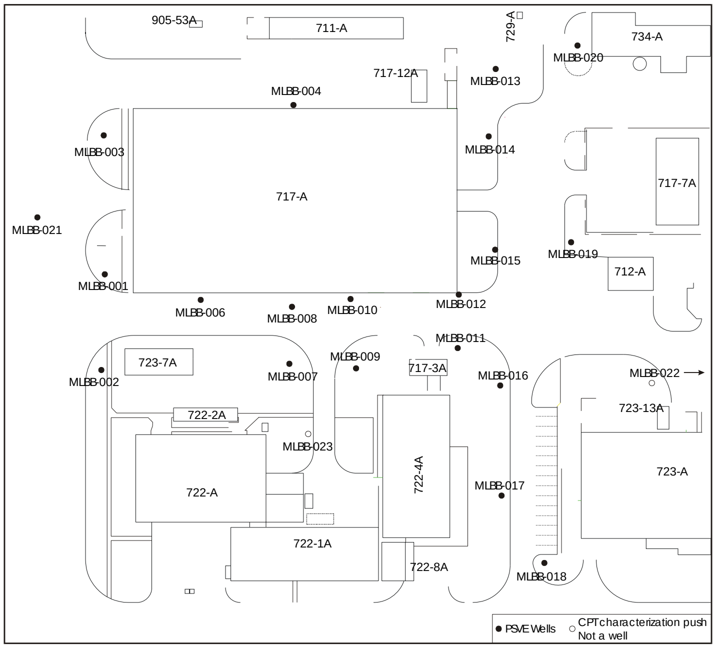


Figure B.1.1: PSVE System Layout for Metlab Site.

B.1.2 PSVE System Description

- ***System Layout:*** Nineteen vadose zone wells were installed across the source area of the Metlab in 1996 using direct push in combination with CPT (Figure B.1.1).

- ***Screened Interval:*** PSVE wells were screened continuously from 20 to 80 ft bgs.

- ***System Design:*** BaroBall^{TM} devices were installed on the upper end of each well casing to permit passive soil vapor extraction via natural barometric pressure changes.

- ***Monitoring Period:*** Monitoring of well vapor concentrations (PCE and TCE) began in June 1998 and has continued to date.

B.1.3 Results/Performance Metrics

Performance data for the Metlab is available through June 2005 (Riha, 2005c). It includes temporal concentration trends, mass removal rates, plume size, and cumulative mass removal, as summarized in Table B.1.

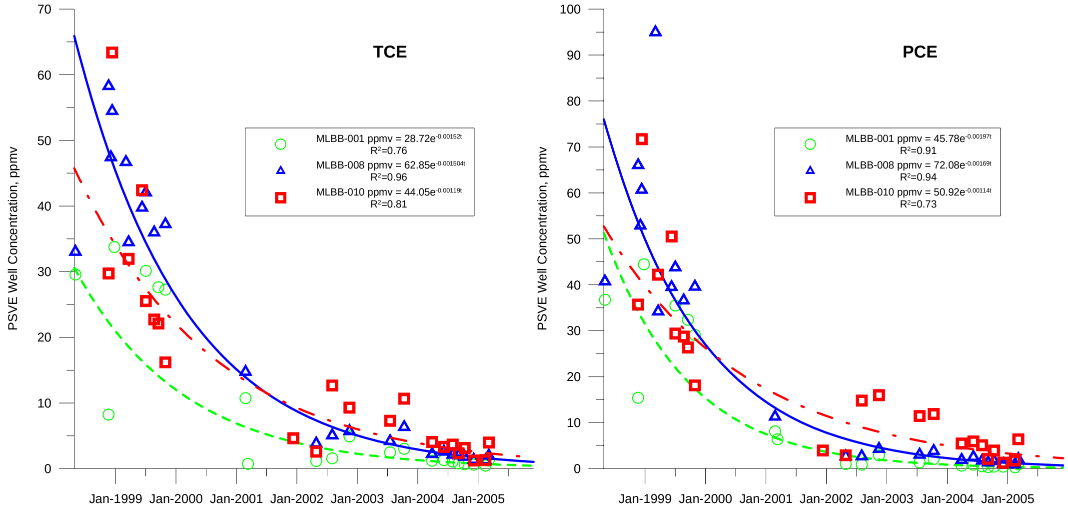


Figure B.1.2: Vapor-Phase Concentration Trends at Metlab Site during PSVE System Operation.

Concentration Trends:

- Soil gas PCE and TCE in wellhead samples exhibited decreasing concentration trends in all wells. The PSVE system resulted in order of magnitude or greater concentration reduction in the majority of wells, with levels near or below 1 ppmv by June 2005 (Figure B.1.2). During the monitoring period, the average PCE gas-phase concentration decreased from 18.0 to 0.8 ppmv and the average TCE gas-phase concentration decreased from 15.4 to 0.7 ppmv.

- The trend was exponential as was expected based on a conceptual model of mass transfer from the liquid phase in the fine-grained soils to the gas phase of the coarse-grained soils.

- Strong correlations were obtained when the data were exponentially fitted, with decay coefficients ranging from 0.0006 to 0.0020 yr^{-1} for PCE and 0.0004 to 0.0016 yr^{-1} for TCE. In effect, these decay coefficients serve as mass removal rates and can be used to estimate future mass removal by PSVE.

Plume Size:

- Both the PCE and TCE plumes shrank considerably during the PSVE operation, receding towards the source area at the south side of Building 717-A, confirming that mass removal by the PSVE controlled plume migration at the Metlab.

- The area where soil gas concentrations exceed 1 ppmv decreased at least 50% relative to initial conditions.

Cumulative Mass Removal:

- The nineteen PSVE wells with Baroball™ devices removed between 0.66 and 24.99 lb of PCE and between 0.19 and 19.29 lb of TCE in the period between June 1998 and June 2005. Wells with low cumulative mass removals initially had low gas-phase concentrations.

- In total, these wells removed 163.51 lb of PCE and 104.77 lb of TCE during this seven-year period. In all cases, mass removals were estimated using the gas phase concentrations along with the average flow rate from the PSVE wells (approximately 1 cfm).

Table B.1: Summary of Relevant Data for MetLab Site

Site Name	MetLab
Location	Savannah River Site, Aiken, SC
Type of Device Utilized	Baroball™
No. of Wells	19
No. of Wells per acre	6 (estimated)
Zone of Capture	25 ft (assumed based on well spacing)
Screened Interval	60 ft (from 20 to 80 ft bgs)
Average Flow Rate	1 cfm
Pore Volumes Removed During Operating Period	Not reported
Starting Vapor-Phase Concentration	18.0 ppmv PCE 15.4 ppmv TCE (Average of 19 wells)
Ending Vapor-Phase Concentration	0.8 ppmv PCE 0.7 ppmv TCE (Average of 19 wells after 7 years of operation)
Mass Transfer/Removal Rate (per well)	0.0006 to 0.0020 yr^{-1} PCE 0.0004 to 0.0016 yr^{-1} TCE
Mass Removed (per well)	0.66 to 24.99 lb of PCE; 0.19 to 19.29 lb of TCE
Mass Removed (cumulative)	163.51 lb of PCE; 104.77 lb of TCE
Cost	Not reported

B.2 Miscellaneous Chemical Basin (MCB)

Information for the site was drawn primarily from the contract report WSRC-TR-97-00405, entitled *Miscellaneous Chemical Basin Treatability Study: An Analysis of Passive Soil Vapor Extraction Wells (PSVE).* The report is publicly-available and can be downloaded at http://www.osti.gov/bridge/servlets/purl/574514-ehlVmz/webviewable/. Additional information was obtained from the authors of the report.

B.2.1 Site Description

- ***Location:*** The Miscellaneous Chemical Basin (MCB) waste unit is located at the Savannah River Site (SRS), in the northwest portion of the site.

- ***Site History:*** Limited information is available concerning historic releases within the MCB, but it is thought that the basin received mixed solvent waste, used oil, and partially full drums until 1974. Afterward, sediments from the basin area were spread across an area approximately 350 ft by 350 ft. These historic releases created vadose zone soil impacts and a soil gas plume. The center of the plume does not correspond to the location of the former basin due to regrading.

- ***Site Hydrogeology:*** The fine-grained soil intervals of interest are approximately 0 to 15 ft and 75 to 85 ft bgs. The water table is encountered at approximately 120 ft bgs.

- ***Pre-Test Conditions:*** Characterization studies (conducted primarily in 1986 and 1996) included extensive soil and soil gas sampling that established the highest concentrations around CPT-MCB-4 in the 15 to 20 ft depth interval. Soil gas concentrations ranged up to 99.5 ppmv PCE and 140 ppmv TCE (in addition to lower concentrations of several other constituents), with evidence of gas plume migration to the southeast. The highest soil concentrations were detected in the vicinity of CPT-MCB-4 and CPT-MCB-S2 and elevated soil concentrations continued to depths of approximately 225 ft, suggesting the release of a source that had migrated into and through two fine-grained units in the vadose zone.

B.2.2 PSVE System Description

- ***System Layout:*** Twenty-five vadose zone wells were installed across the source area of the MCB in 1996 in boreholes where CPT had been completed (Figure B.2.1).

- ***Screened Intervals:*** All wells extended to within 10 ft of the water table and were screened across the sections of the unsaturated zone described above.

- ***System Design:*** Baroball^{TM} devices were installed on the upper end of each well. The devices permit passive soil vapor extraction via natural barometric pressure changes.

- ***Monitoring Period:*** Monitoring of well vapor concentrations (PCE and TCE) began in April 1996 as part of a treatability study that extended for a period of approximately 1 year. Based on the success of this initial study, the system was left in place and continues to operate to this date. An active soil vapor extraction system was also initiated in October 2001 and was terminated in December 2002.

B.2.3 Results/Performance Metrics

Comprehensive performance data for the MCB is available from the treatability study (WSRC, 1997). It includes temporal concentration trends, mass removal rates, plume size, cumulative mass removal, and estimation of remediation timeframe, as summarized in Table B.2. It should be noted that the temporary operation of an ASVE system at the MCB influenced the performance of the PSVE after this period, such that subsequent data would not necessarily reflect long-term performance of a stand-alone PSVE system.

Concentration Trends:

- Soil gas TCE measured directly from wellhead samples exhibited decreasing concentration trends through the first 13 months of monitoring in all wells. The PSVE system resulted in concentration reductions of greater than 50% in the majority of wells during this period (Figure B.2.2).

- This trend was exponential, as was expected based on a conceptual model of mass transfer from the liquid phase in the fine-grained soils to the gas phase of the coarse-grained soils.

- Strong correlations were obtained when the data were exponentially fitted, with decay coefficients ranging from 0.002 to 0.006 yr^{-1} for TCE.

- Based on these mass removal rates, it was projected that PSVE alone would have reduced TCE concentrations to below 1 ppmv within 3 years in the soil gas plume and within 10 years in source zone wells.

Plume Size:

- The size of the TCE plume, as well as the TCE concentrations within the plume, decreased significantly during the 13 month PSVE treatability test. For example, the area where soil gas concentrations exceeded 20 ppmv decreased by at least 50% relative to initial conditions.

- The test demonstrated that PSVE removed sufficient mass to shrink the plume.

Cumulative Mass Removal:

- The 25 PSVE wells with Baroball™ devices removed more than 100 lb of chlorinated organics in the period between October 1996 and November 1997 based on soil gas concentrations and average flow rates from the PSVE wells (2 to 4 cfm).

- Using the exponential mass removal rates, it was estimated that approximately twice this amount would be removed by PSVE in the subsequent 9 years.

- Depth discrete soil samples were collected. Soil concentrations indicated a reduction of 13% in the TCE mass in the fine-grained sediments of the source area during the initial 13 months of PSVE operation.

Remediation Timeframe:

- The authors projected that PSVE would achieve its objective (1 ppmv) within 3 years in plume wells and within 10 years in source zone wells.

- No estimate of the remediation timeframe in the absence of PSVE was presented.

Table B.2: Summary of Relevant Data for MCB Site

Site Name	MCB
Location	Savannah River Site, Aiken, SC
Type of Device Utilized	Baroball™
No. of Wells	25
No. of Wells per acre	0.9 (estimated)
Zone of Capture	120 ft (assumed based on well spacing)
Screened Interval	Selected intervals from 0 to 110 ft bgs
Average Flow Rate	2 to 4 cfm
Pore Volumes Removed During Operating Period	Not reported
Starting Vapor-Phase Concentration	37 ppmv TCE (Average of 19 selected wells)
Ending Vapor-Phase Concentration	13 ppmv TCE (Average of 19 selected wells after 1.1 yr of operation)
Mass Transfer/Removal Rate (per well)	0.001 to 0.006 yr^{-1} TCE
Mass Removed (per well)	Not reported
Mass Removed (cumulative)	100 lb of total chlorinated solvents for first 1.1 yr
Cost	$354 to $709 per lb removed for first 1.1 yr $213 to $427 per lb removed over 10 yr

B.3 M-Area Abandoned Process Sewer Line (MAPSL): BaroBall™

Information for the site was drawn primarily from the contract report WSRC-TR-2004-00143, entitled *Performance Testing of Passive Soil Vapor Extraction (PSVE) along the M-Area Abandoned Process Sewer Line (MAPSL).* The report is publicly-available. Additional information was obtained from the authors of the report.

B.3.1 Site Description

- ***Location:*** The M-Area Abandoned Process Sewer Line (MAPSL) is located at the Savannah River Site (SRS). It is approximately 2000 ft long and connects the former M-Area security fence and the M-Area Settling Basin.

- ***Site History:*** The original MAPSL was 30-inch diameter vitrified clay tile. Cracks at pipe connections resulted in several point-source releases of CVOCs (primarily PCE and TCE) to the underlying unsaturated zone. A 12inch polyethylene pipe was installed in the 30-inch clay tile to minimize leakage. Sewer line use ceased in 1985.

- ***Site Hydrogeology:*** At the MAPSL, the fine-grained soil intervals of primary interest are thin clays located approximately 40 ft and 65 ft bgs, and interbedded sands and clays encountered at 95 ft bgs and extending below the water table, which is approximately 135 ft bgs. In addition, the “upland unit” (a low permeability soil mix of sand, silt, and clay) extends to 40 ft bgs in the MAPSL area.

- ***Pre-Test Conditions:*** To address vadose zone contamination, three active soil vapor extraction (ASVE) units were installed and operated at the MAPSL starting in 1995. Characterization studies conducted primarily in 2000 established that the ASVE systems had effectively cleaned up the central sandy unit but that contaminant removal from lower permeability zones was limited. Residual PCE, TCE, and 1,1,1-TCA remained in the fine-grained intervals, including the upland unit. Of particular concern was the central section of the MAPSL that was part of SVE unit 782-8M. Additional characterization in 2003 encountered DNAPL in two borings in the upland unit at depths between 20 and 26 ft bgs.

B.3.2 PSVE System Description

- ***System Layout:*** A total of 8 of the ASVE wells were switched to PSVE in the period between November 2001 and April 2003 as a low-energy alternative to recover residual contamination from the fine-grained units of the unsaturated zone while preventing migration to the groundwater (Figure 5.3.1). Two new PSVE wells were installed in October 2003. The ASVE system was not used after 2001. .

- ***Screened Intervals:*** The eight wells retro-fitted with BaroBall^{TM} devices were screened continuously from 25 to 110 ft bgs. The two new PSVE wells installed in October 2003 targeted a short soil interval (30 to 40 ft bgs) of permeable soils to address DNAPL in fine-grained soils located immediately above them.

- ***System Design:*** Baroball^{TM} devices were installed on the upper end of the well casing of the 8 original wells to permit passive soil vapor extraction via natural barometric pressure changes. These wells are all located in the upper and central sections of the MAPSL. One of these wells (MVE-24) was abandoned in October 2003. The two new PSVE wells installed in October 2003 were equipped with MicroBlower devices (see Section B.4).

- ***Monitoring Period:*** Monitoring of well vapor concentrations began in November 2001 for the wells equipped with Baroball^{TM} devices. The system continues to operate through the present date. Three additional vent wells located in the lower section of the MAPSL were converted to sweep wells to increase subsurface flow towards the vapor extraction wells. (Sweep well use was discontinued in 2003 in preparation for steam stripping remediation planned near the M-Area Settling Basin).

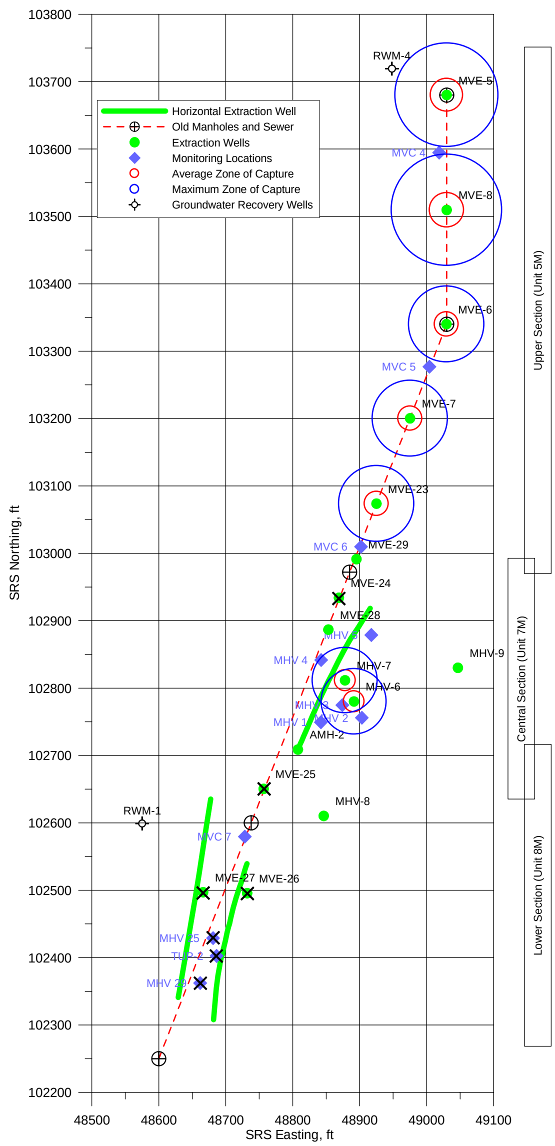


Figure B.3.1: PSVE System Layout for MAPSL Site.

B.3.3 Results/Performance Metrics

Performance data for the MAPSL is available through early 2005 (WSRC, 2005). It includes temporal concentration trends, cumulative mass removal, zone of capture, and mass transfer rates (including relative to diffusion rates) to prevent migration to the water table, as summarized in Table B.3. Performance for the 2 wells where MicroBlowers were installed is summarized in Section B.4.

Concentration Trends:

- In general, PCE and TCE soil gas concentrations increased until late 2003 and then declined through the remainder of the monitoring period (Figure B.3.2).

- Three theories were postulated for the long-term trends of increasing then decreasing concentrations: i) subsurface concentration equilibration after transition from ASVE to PSVE; ii) increased efficiency of PSVE due to decreased vertical permeability from rainfall; and iii) increases in measured well vapor concentration due to contaminated water infiltration into the central sandy zone from the upland unit.

- Depth discrete gas data from piezometers screened in the fine-grained intervals was collected during the period when ASVE was halted and following PSVE operation to monitor rebound effects. The shallowest depths (50 and 75 ft bgs) showed the expected decrease in concentration during ASVE operation and the expected increase during system shutdown and PSVE. This zone provides a long-term contaminant source that was not directly addressed by the ASVE.

- The data show that gas concentrations are near or at equilibrium with the source areas in the fine-grained zones and that PSVE is decreasing concentrations in the upper and lower vadose zone, while concentrations in the middle vadose zone are stable.

- In the deep vadose zone (deeper than 100 ft bgs), concentrations are lower than the shallow vadose zone, indicating the ASVE was effective in cleaning the lower section and the PSVE is reducing downward migration of contaminants.

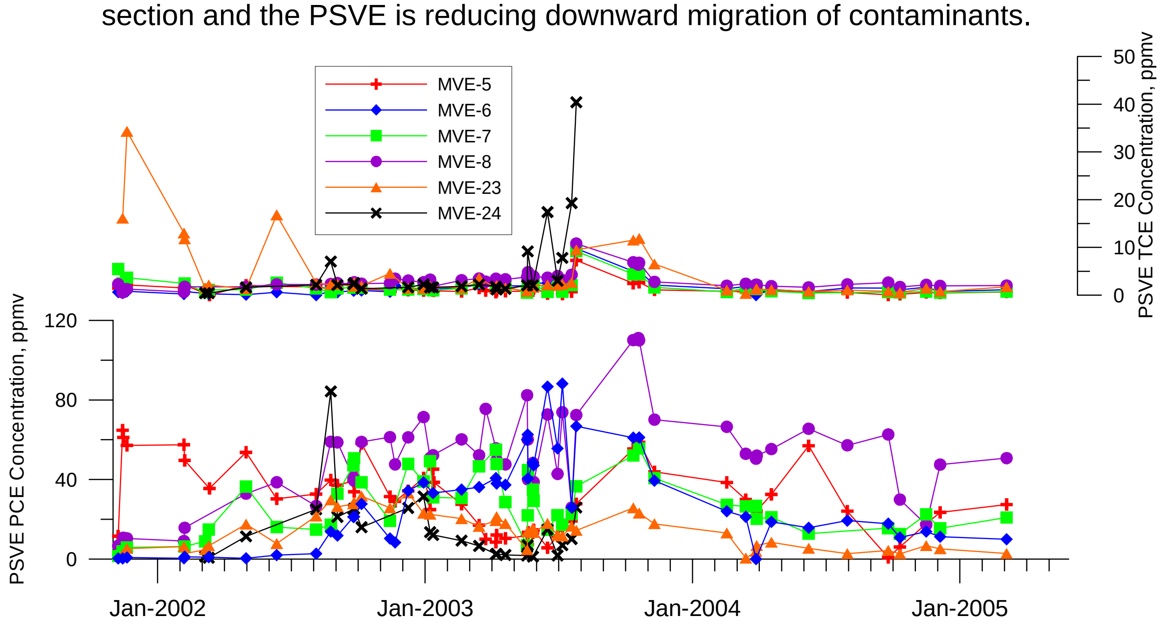


Figure B.3.2: Vapor-Phase Concentration Trends at MAPSL Site during PSVE System Operation (6 PSVE Wells with Baroball™ devices).

Cumulative Mass Removal:

- The seven PSVE wells with BaroBalls removed between 15.2 and 316.7 lb of PCE and between 3.2 and 17 lb of TCE between November 2001 and April 2005. Five of these wells were operational for the entire period, while two were operational only during the final two years.

- In total, these wells removed 676.1 lb of PCE and 64.4 lb of TCE.

- In all cases, mass removals were estimated using the gas phase concentrations along with the average flow rate from each of the PSVE wells (2.6 to 7.5 cfm, with a maximum of 76.2 cfm) using differential pressure data.

Zone of Capture:

- The zone of capture (ZOC), defined as the radius of the volume of soil gas removed during a flow event, was 16 to 26 ft for a subset of wells using one year of flow event data. A second method generated average ZOC values between 9 and 39 ft.

- Due to the pulsed nature of the flow events, several estimation methods were used, differing in the period of time over which well flow rates were measured.

- The authors stated that the calculated ZOC and flow rates alone were not adequate to define the effectiveness of PSVE, and that consideration should be given to concentration trends in the vicinity of the well to determine if coverage is adequate.

Mass Transfer Rates:

- It was determined that 0.053 lb/day of PCE and 0.048 lb/day of TCE were being released from the fine-grained soils, while the PSVE system (i.e., wells with BaroBalls) was removing 0.06 to 0.07 lb/day of PCE and TCE. This mass transfer from fine-grained soils was calculated from data collected during a rebound test conducted at a series of wells with depth discrete screens in 2002 after ASVE was stopped and as the subsurface contaminant distribution approached equilibrium prior to the start of the PSVE system.

- This demonstrated that PSVE was removing what was being released and thus was protecting the groundwater.

- Further attempts at establishing that mass transfer to the water table was not occurring used a combination of numerical and analytical modeling to establish that the pore water velocities generated by PSVE (3.29×10^{-6} to 5.78×10^{-4} cm/s) were larger than the downward diffusion rates (1.38×10^{-8} to 1.82×10^{-6} cm/s).

Table B.3: Summary of Relevant Data for MAPSL Site (Baroball™ PSVE Wells)

Site Name	MAPSL
Location	Savannah River Site, Aiken, SC
Type of Device Utilized	Baroball™
No. of Wells	8
No. of Wells per acre	0.3 (estimated)
Zone of Capture	16 to 26 ft (using 1 yr of flow event data); 9 to 39 ft (using continuous average flow rate)
Screened Interval	85 ft (25 to 110 ft bgs)
Average Flow Rate	2.6 to 7.5 cfm (maximum of 76 cfm)
Pore Volumes Removed During Operating Period	Not reported
Starting Vapor-Phase Concentration	~ 45 ppmv PCE ~ 5 ppmv TCE (Average of 5 wells at peak following switch to PSVE system)
Ending Vapor-Phase Concentration	~15 ppmv PCE < 2 ppmv TCE (Average of 5 wells following 4.5 yr of operation)
Mass Transfer/Removal Rate (per well)	0.06 to 0.07 lb/day TCE; 0.06 to 0.07 lb/day PCE; (Average of 2 wells)
Mass Removed (per well)	15.2 to 316.7 lb of PCE; 3.2 to 17.0 lb of TCE
Mass Removed (cumulative)	676.1 lb of PCE; 64.4 lb of TCE
Cost	Not reported

B.4 M-Area Abandoned Process Sewer Line (MAPSL): MicroBlower

MicroBlower operation at the MAPSL site was reported by the project team which conducted the project (Washington Savannah River Company). Because the report is not publicly-accessible, additional detail is presented herein.

B.4.1 Site and PSVE System Description.

- As described in Section B.3, three ASVE units have targeted vadose zone chlorinated solvent contamination along this 1500 ft section of the MAPSL since 1995. In 2002, all ASVE operations were shutdown and passive soil vapor extraction began. In 2003, characterization activities indicated that residual contamination remained in the fine-grained sediments at two locations along the MAPSL. Specifically, DNAPL was found in two borings completed in the shallow, fine-grained sediments (20 to 26 ft bgs) that are part of the upland unit.

- In February 2004, MicroBlowers were installed at these two locations (MVE-28 and MVE-29, Figure B.3.1) to target small areas of contamination and to minimize contaminant transfer to the groundwater. The original MicroBlower design was a 12 V system powered solely by a solar panel. These systems were capable of extracting contaminant mass only when the sun was shining, and therefore operated on a periodic basis. In January 2006, 24 V MicroBlower systems were installed. These systems are designed to operate 24 hours a day using a sustainable 24 V power source (a battery bank charged by solar panels). The two enhanced PSVE wells are screened 30 to 40 ft bgs in relatively permeable soil that underlie the fine-grained sediments where DNAPL was found.

B.4.2 Results/Performance Metrics

Performance at the MAPSL site following the installation of the 24 V MicroBlower system is summarized in Table B.4.

Concentration Trends:

- The periodically-operating 12 V MicroBlower system did not reduce CVOC vapor concentrations, but as shown in Figure B.4.1, PCE and TCE vapor-phase concentrations decreased rapidly and stabilized at a lower level following the switch to the continuously-operating 24 V system in January 2006.

- Soil concentration profiles from sampling events completed in 2003 (prior to MicroBlower installation) and in 2007 (post-installation) are shown in Figure B.4.2. Soil concentrations of both PCE and TCE decreased by an order of magnitude in the interval immediately above the screened zone of the extraction well. This interval consists of fine-grained material, as indicated by the higher CPT (cone penetrometer test) friction ratios measured as part of the characterization study. Interestingly, the enhanced PSVE system significantly reduced contaminant levels in the fine-grained interval despite the fact that it has the tendency to trap contaminant mass and DNAPL was present.

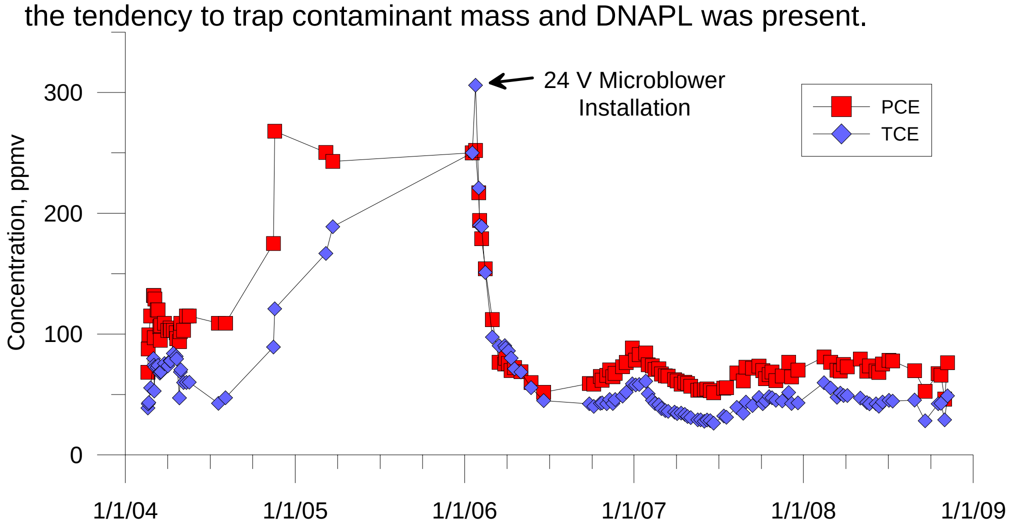


Figure B.4.1: Vapor-Phase Concentration Trends at MAPSL Site during PSVE System Operation (PSVE Well MVE-29 with MicroBlower).

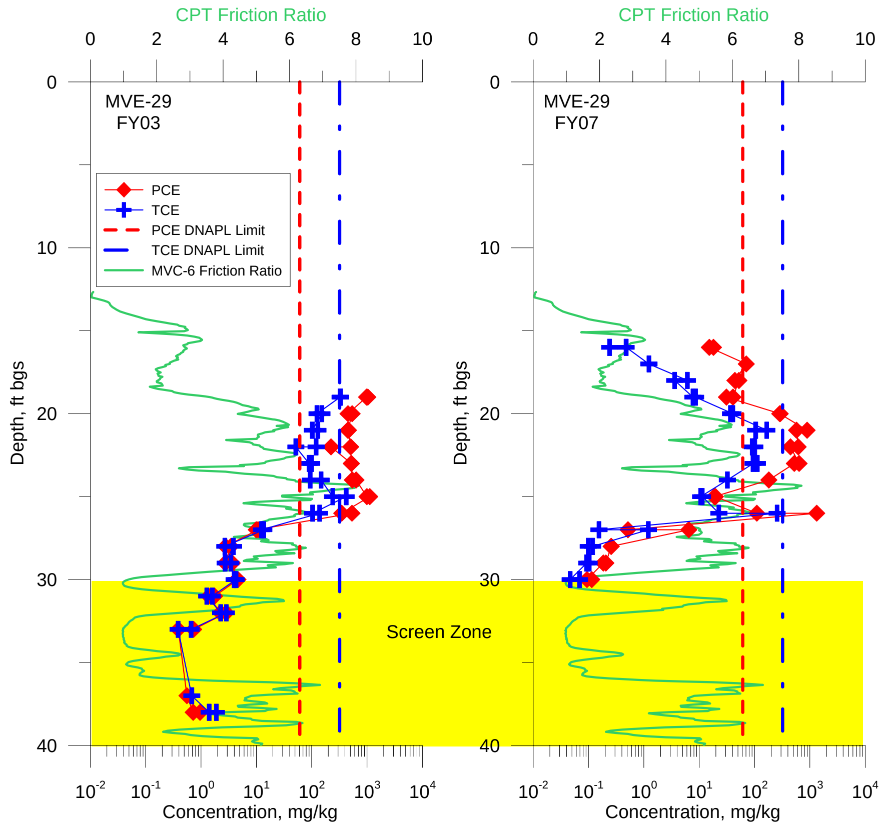


Figure B.4.2: Soil Concentration Profiles at MAPSL Site during PSVE System Operation. Samples Collected at PSVE Well MVE-29 Before and After Installation of MicroBlower.

System Operational Parameters:

- MicroBlower operational parameters have been recorded since deployment (Figure B.4.3). Battery voltage shows a diurnal pattern with the daytime voltages increasing up to 28 V as a result of solarization and an increase in power provided by the solar panel. During night time hours, the battery voltage slowly decreases, with corresponding decreases observed in the flow rate and vacuum. The MicroBlower is designed to operate 24 hours a day, but on occasion, the system will shut down due to prolonged periods of overcast skies. The system response during this type of incident is shown on Figure B.4.3 on May 7, 2007, where voltage decreased sharply and shutdown eventually occurred after 3 days of cloudy skies. Note that the battery charger for this system has a low voltage shutoff to protect the batteries from excess damaging discharge. During the entire operating period, the average flow rate was approximately 2 scfm, and the vacuum consistently fell between 6 and 8 in. H_2O.

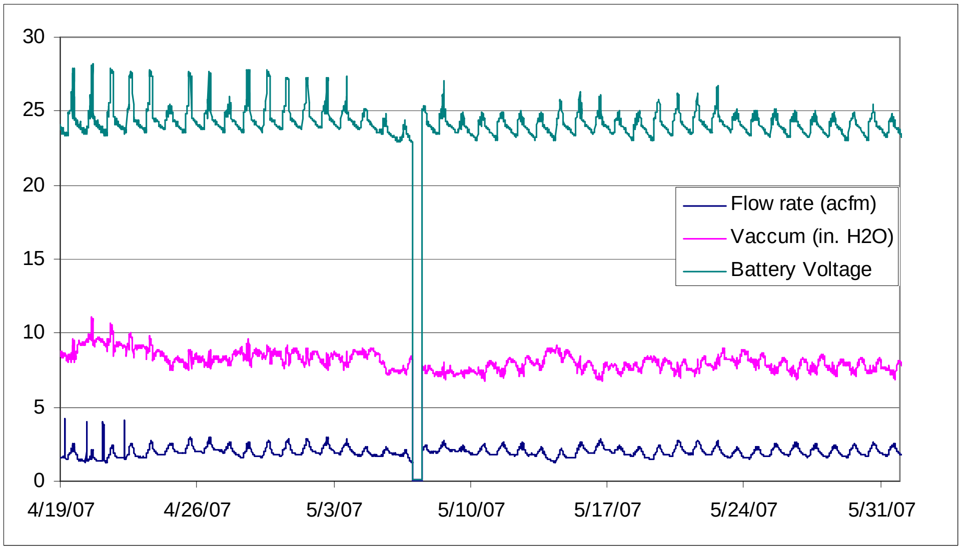


Figure B.4.2: MicroBlower Operational Parameters at MAPSL Site during PSVE System Operation (PSVE Well MVE-29).

Cumulative Mass Removal:

- Forty-seven pounds of TCE and eighty-two pounds of PCE were recovered from Well SVE-29 during the period starting January 17, 2006 and ending November 6, 2008. The linear profiles of these curves indicate that the MicroBlower system is treating the DNAPL source zone above the screen. It is anticipated that once the DNAPL is depleted, vapor concentrations (Figure B.4.1) will decline, resulting in decreased mass removal rates relative to system startup.

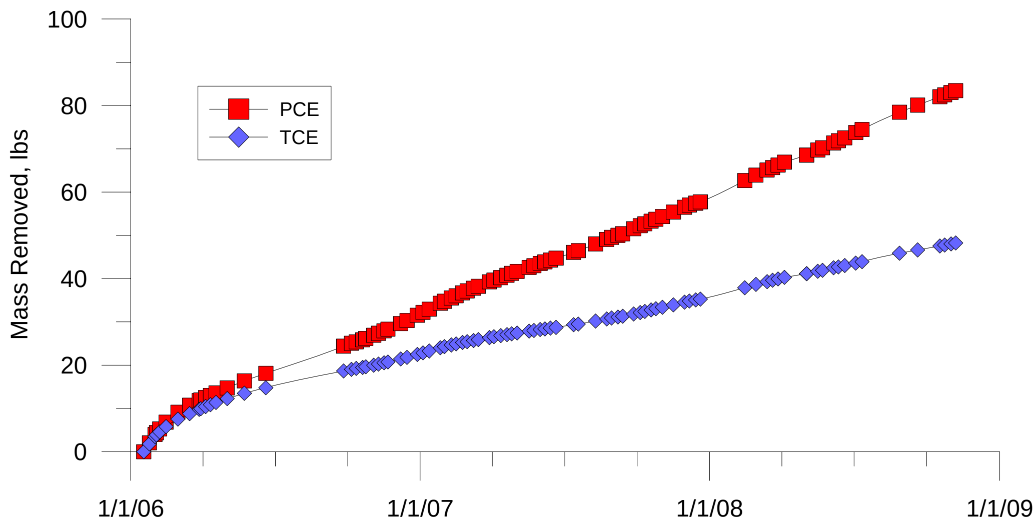


Figure B.4.4: Cumulative Mass Removal at MAPSL Site during PSVE System Operation (PSVE Well MVE-29 with MicroBlower).

Table B.4: Summary of Relevant Data for MAPSL Site (MicroBlower PSVE Wells)

Site Name	MAPSL
Location	Savannah River Site, Aiken, SC
Type of Device Utilized	MicroBlower
No. of Wells	2
No. of Wells per acre	0.8 (estimated)
Zone of Capture	Not Reported
Screened Interval	10 ft (30 to 40 ft bgs)
Average Flow Rate	2 cfm (Data from 1 well)
Pore Volumes Removed During Operating Period	Not reported
Starting Vapor-Phase Concentration	250 ppmv PCE 300 ppmv TCE (Data from 1 well)
Ending Vapor-Phase Concentration	60 ppmv PCE 40 ppmv TCE (Data from 1 well)
Mass Transfer/Removal Rate (per well)	0.12 lb/day PCE; 0.07 lb/day TCE; (Data from 1 well)
Mass Removed (per well)	82 lb of PCE; 47 lb of TCE
Mass Removed (cumulative)	Not reported
Cost	Not reported

B.5 Multiple Demonstration Sites in Denmark

Information for these sites was drawn primarily from a project report (Nr. 805 2003), entitled *Passiv ventilation til fjernelse af PCE fra den umttede zone—Hovedrapport (Passive ventilation for remediation of PCE from unsaturated zone).* The Danish language report (with an English language executive summary) is publicly-available and can be downloaded at http://www2.mst.dk/Udgiv/publikationer/2003/87-7972-610-0/pdf/87-7972-611-9.pdf.

B.3.1 Site Descriptions and PSVE System Descriptions

Passive soil vapor extraction was selected for a vadose zone technology demonstration at a series of sites in Denmark. The project was a cooperative effort between the Danish EPA and the counties of Sotrtrøm, Frederiksborg, and Ribe. The performance at 4 of these sites, all former dry-cleaners with PCE and other chlorinated solvents present in a highly permeable sand interval that underlies a clay cover, was documented after 18 to 24 months of operation (Christensen et al., 2003), and a compilation of the results is found in Table B.4. At all of these sites, the PSVE process utilized a one-way valve connected to a well screened across the unsaturated zone, followed by an in-line granular activated carbon unit for treatment of the off-gas prior to venting At one site (Fakse), a solar-powered vacuum pump was installed on one of the wells. The pump increased extraction rates approximately 5 times over passive flow rates.

Table B.4: Summary of Relevant Data for 4 Sites in Denmark

Site Names	(1) Møllevej 12, Askov; (2) Nygade 37, Fakse; (3) Prins Valdemars Alle 14, Allerød; (4) Amtsvej 2-4, Allerød
Location	Counties of Sotrtrøm, Frederiksborg, and Ribe in Denmark
Type of Device Utilized	One-way valve for flow control, coupled with granular activated carbon treatment of off-gases
No. of Wells	Varies, typically 5 to 6 per site
No. of Wells per acre	Varies
Zone of Capture	3 to 13 ft average; 10 to 33 ft maximum
Screened Interval	Varies, but typically across entire unsaturated interval to approx. 60 ft bgs
Average Flow Rate	0.1 to 0.6 cfm
Pore Volumes Removed During Operating Period	25 to 100 during 2 yr operating period
Starting Vapor-Phase Concentration	100 to 300 mg/m3 PCE (Average)
Ending Vapor-Phase Concentration	30 to 120 mg/m3 PCE (Average of wells after up to 2 yr of operation)
Mass Transfer/Removal Rate (per well)	0.2 to 2.2 lb/yr PCE
Mass Removed (per well)	Not reported
Mass Removed (cumulative)	4 to 6 lb; 11 lb; 18 lb; 110 to 130 lb
Cost	~ $35,000 to $45,000 for typical site with 5 to 6 wells (converted from Danish Krone; excluding value-added tax)