



United States  
Environmental Protection  
Agency

EPA/600/R-18/053 | February 2018 | [www.epa.gov/research](http://www.epa.gov/research)

# Engineering Issue: Soil Vapor Extraction (SVE) Technology

Office of Research and Development  
National Risk Management Research Laboratory  
Land and Materials Management Division

## Soil Vapor Extraction (SVE) Technology

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### 1 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) Engineering Issue Papers (EIPs) are a series of technology transfer documents that summarize the latest information on selected waste treatment and site remediation technologies and related issues. The information is presented in a conveniently accessible manner to the user community. EIPs are designed to help remedial project managers (RPMs), on-scene coordinators (OSCs), contractors, and other practitioners understand the type of data and site characteristics needed to evaluate a technology for a specific site, as well as ways to design and optimize a technology for a particular application. Each EPA EIP is developed in conjunction with a small group of engineers and scientists from inside EPA and outside consultants, with a reliance on peer-reviewed literature, EPA reports, Web sources, current ongoing research, and other pertinent, available, and verifiable information.

This EIP assembles, organizes, and summarizes the current knowledge on soil vapor extraction (SVE) technologies that are available for removing volatile organic compounds (VOCs) from unsaturated soils

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above the water table. As a technical support document, it describes SVE technologies with a focus on remedial scoping needs, but it does not represent EPA policy or guidance.

### Key Updates to the SVE EIP

- SVE testing as a component of site characterization at VOC-contaminated sites (Section 3)
- Pilot testing and adaptive SVE implementation (Section 4.1)
- Rebound evaluation for assessing cleanup progress (Section 5.3)
- Transitioning and implementing SVE for vapor intrusion mitigation (Section 5.4)
- Relating mass transfer constraints quantified during SVE to vapor intrusion and groundwater impacts (Section 6)

## 1.1 Purpose

This document summarizes the state-of-the-science regarding the widespread use of SVE as a major treatment technology for removing VOCs from soil. SVE can be applied alone or as an integral component of more complex remedial technologies that volatilize subsurface contaminants (e.g., thermal remediation, air sparging). This EIP provides updated information since the issuance of the original Engineering Bulletin (U.S. EPA, 1991a) and two Engineering Forum Issue Papers (U.S. EPA, 1996a, 1997b) on SVE. It provides information describing SVE and its applicability and limitations; site characterization; design and construction; performance monitoring, evaluation, optimization, and shutdown; complementary technologies; costs; case studies; and references for further information. Key updates are described in the text box above.

To stay concise, this EIP summarizes relevant information and provides references and Web links for more in-depth material. These Web links, although verified as accurate at the time of publication, are subject to change.

## 1.2 Background

SVE is an in situ technology widely used in commercial remediation for more than 25 years. SVE is generally a cost-effective remediation process for gasoline, solvents, and other relatively volatile compounds. SVE has been the industry default remedy for VOCs in soils for more than 20 years (U.S. EPA, 1993, 1996b) and the technology has been chosen as a component of the remediation plan at

more than 285 Superfund sites (U.S. EPA, 2012a). SVE can be used alone to physically remove VOCs from unsaturated (vadose zone) soils, but it is often used with other technologies that enhance biodegradation (for biodegradable VOCs), volatilization, or both. For example, air injection into the underlying groundwater accompanied by SVE is known as air sparging (U.S. EPA, 2001). During thermal remediation, SVE is a key component for capturing volatilized contaminants (U.S. ACE, 2014).

Typical petroleum hydrocarbon releases occur at retail gasoline stations and bulk fuel transfer facilities through leaking underground storage tanks and piping. In these situations, the contaminant usually exists as a lighter-than-water nonaqueous phase liquid (LNAPL) that disperses in the vadose zone according to geology. If sufficient fuel is released, pools of LNAPL can collect atop low permeability strata and the water table. In this scenario, SVE is integral to multiphase extraction that simultaneously performs vacuum-enhanced extraction/recovery to remove free-phase LNAPL from the water table, vapor extraction to remove volatile vapors, and aeration (bioventing) to stimulate biodegradation (U.S. ACE, 1999; U.S. EPA, 1996c). SVE alone can be effective at removing significant contaminant mass but can take a long time. As the most volatile compounds such as benzene are preferentially stripped from the LNAPL, the overall LNAPL volatilization rate diminishes exponentially over time, slowing the progress towards cleanup goals. When this occurs, transitioning from SVE to a more cost-effective technology such as bioventing or biosparging is a common optimization step.

Chlorinated solvents are typically released into the subsurface through solvent spills, poor storage practices, or accidental releases of water contaminated with dissolved solvents (e.g., overflow of a NAPL/water separator). Chlorinated solvents differ from petroleum hydrocarbons in that they do not readily biodegrade in the subsurface (U.S. EPA, 2012b). Because they do not easily biodegrade, they can travel through the subsurface with water and by vaporous

diffusion over extended times and distances, resulting in long plumes and a significant mass of dissolved and adsorbed chlorinated compounds sequestered in fine-grained soils. In this scenario, VOC mass extraction during SVE rapidly becomes limited by the rate of contaminant migration out of the fine-grained soils and into the path of soil gas flowing to the extraction point. Even as the rate of mass removal is largely diminished, subsurface transport of the remaining mass may pose an unacceptable source of contamination for vapor intrusion into buildings or underlying groundwater under ambient conditions. The existence of chlorinated solvents as a denser-than-water NAPL (DNAPL) in the subsurface generally requires a more aggressive source reduction technology than SVE alone.

Basic descriptions of SVE can be found in various online sources (e.g., Federal Remediation Technologies Roundtable [FRTR], 2008; U.S. EPA, 2012a). U.S. EPA (2010) outlines green remediation best management practices for SVE and air sparging technologies. The SVE information in this EIP draws on numerous publications containing details on the design, implementation, and evaluation of SVE since the issuance of the Engineering Forum Issue Papers (U.S. EPA, 1996a, 1997b). These publications include U.S. EPA (2001), Air Force Center for Environmental Excellence (AFCEE, 2001), U.S. Army Corps of Engineers (U.S. ACE, 2002), and U.S. Department of Energy (U.S. DOE, 2013). Additional references for details on various topics are provided throughout this document.

### 1.3 Overview of SVE

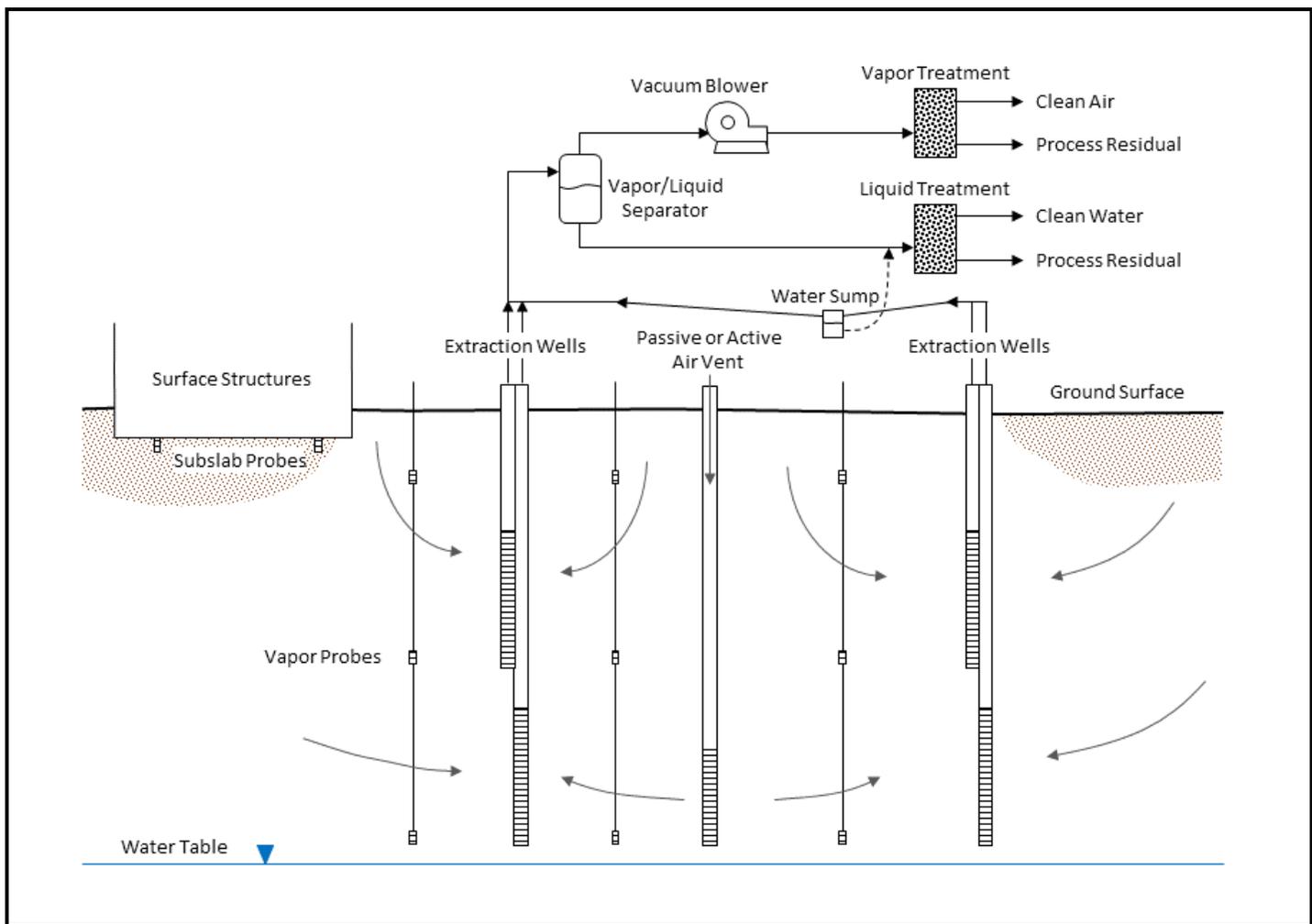
SVE is an attractive treatment technology for VOCs such as gasoline and chlorinated solvents because the soil is treated in place, sophisticated equipment is not required, and the cost is typically lower than other remedial options. Favorable conditions for SVE include:

- Low to moderate soil organic matter content

- Moderate to high permeability soils
- Low to moderate soil moisture
- Modest heterogeneity (e.g., sandy soils interlayered with thin fine-grained units)
- Moderate to deep depth to groundwater (e.g., 5–100 ft).

SVE applies a vacuum to vertical or horizontal wells screened in unsaturated (vadose) zone soils to induce airflow through the contaminated soil. **Figure 1** illustrates a general schematic of the in situ SVE process and its components. Clean air enters soil where contaminants reside and carries volatilized contaminants to the extraction wells. In this way, the gases in the soil are flushed, or exchanged, continuously to increase the volatilization rate of contaminants. Without the application of a vacuum, the soil gas is relatively stagnant and volatilized contaminants migrate slowly into groundwater or to the ground surface as vapors in soil gas. After entering groundwater, VOC contaminants pose a risk to drinking water supplies. Where buildings overlie contaminated soil and groundwater, VOC vapors in soil gas can collect beneath them, enter the buildings, and pose an inhalation hazard.

The introduction of clean air into VOC-contaminated soil volatilizes contaminants for extraction, thereby reducing the overall contaminant mass in soils. A vacuum blower supplies the motive force by inducing gas flow throughout the contaminant vapor plume as illustrated in **Figure 1**. Extracted VOC vapors are separated from condensed water in an air/water separator before or after the blower. The blower discharge then carries the contaminated vapors to a surface off-gas treatment system prior to atmospheric discharge. Typical SVE off-gas treatment consists of contaminant adsorption onto granular activated carbon when concentrations are low or destruction by catalytic or thermal oxidation for higher concentrations (AFCEE, 2001; U.S. ACE, 2014; U.S. EPA, 2006).



**Figure 1.** Process schematic of SVE

The continual flushing of air through the contaminated soil matrix occurs primarily in permeable soils and the initial rate of contaminant removal diminishes rapidly with the reduction of VOC mass in more permeable soils. Slower rates of VOC transport in less permeable soils (where soil gas does not flow) then result in a transition from advection- to diffusion-limited removal.

The primary factors in designing a cost-effective off-gas vapor treatment system are the initial contaminant mass in more permeable and less permeable soils, the rate of contaminant removal, and the contaminant's subsequent decay over time. These parameters can be difficult to predict a priori, and introduce uncertainties to system design economics (e.g., Will off-gas treatment by thermal oxidation be required for a month, a year, or longer? Or is activated carbon

with several frequent exchanges upfront more cost effective?). Further complications are posed by whether contaminants exist as LNAPL, such as gasoline, or DNAPL, such as pure dry-cleaning solvents. Changing conditions in mass extraction during SVE are usually addressed in periodic efforts to optimize the system with respect to costs and attainment of cleanup goals (AFCEE, 2001).

In addition, determining the endpoint for SVE operations is complex when considering the potential impact of residual contaminant mass on underlying groundwater and overlying buildings or recontamination of the vadose zone by underlying contaminated groundwater (U.S. DOE, 2013). The potential and conditions for transitioning SVE systems from vadose zone remedies to vapor intrusion mitigation is a topic of current EPA study

(Lutes et al., 2017; Schumacher et al., 2017; Truesdale et al., 2016) and is discussed in Section 5. Recently developed methodologies for evaluating the impact of residual mass in the vadose zone with respect to site-specific cleanup objectives are reviewed in Section 6.

## 2 SVE APPLICABILITY

For decades, SVE has effectively been used to remove VOCs from the vadose zone in many settings; however, this does not guarantee SVE will achieve acceptable VOC removal at all sites. The performance of SVE technology depends on site-specific characteristics (e.g., soil gas permeability, initial contaminant mass, contaminant mass distribution) that are often difficult to predict from conventional site characterization data alone. However, three general categories of information can be used to assess the applicability of SVE to a particular site:

- **Contaminant type and phase:** How amenable are the specific contaminants for removal by SVE, aerobic degradation, or both? Do contaminants exist as an LNAPL or a DNAPL?
- **Site characteristics:** How well can an SVE system induce significant air flow through the contaminated soil matrix given a site's hydrogeologic properties (e.g., permeability, moisture content, heterogeneity), depth to contaminant and to groundwater, and surface obstructions to equipment placement?
- **Performance objectives:** What are the site remediation goals, expressed as concentration or mass flux reductions in specific volumes and within specific time frames?

The following sections describe how to answer these questions and decide whether SVE is applicable at a specific site.

### 2.1 Contaminant Type and Phase

In general, SVE is applicable to compounds that volatilize (from water or NAPL) into soil gas at concentrations that yield significant mass removal rates relative to the mass in the soil. Important contaminant properties that relate to assessing the suitability of SVE at a given site include vapor pressure, solubility, Henry's law constant, octanol-water partition coefficient, air and water diffusivities, and aerobic biodegradation rates. U.S. EPA (1996d) describes most<sup>1</sup> of these parameters and provides values for most VOCs of interest at SVE sites. How these properties affect contaminant fate and transport and SVE performance, is described briefly below.

- **Vapor pressure** provides information on a compound's volatility. With respect to SVE, higher vapor pressures (and low solubility) allow for faster extraction of contaminant mass. For compounds with lower vapor pressures, and adequate aerobic biodegradation rates, bioventing may be more suitable than SVE.
- **Solubility** is the tendency of compounds to dissolve in porewater. With higher solubility, moist vadose zone soils retain a higher dissolved mass in the soil porewater.
- **Henry's law constant ( $H$ )** is defined as the ratio of a chemical's equilibrium partial vapor pressure in the gas phase to its dissolved (aqueous-phase) concentration. SVE applicability increases with increasing Henry's constant as the compound increasingly prefers the gas phase, and Henry's constant is more important than vapor pressure for evaluating SVE suitability. For example, methyl tertiary butyl ether (MTBE) is volatile (high vapor pressure) but has a very low Henry's constant, indicating a high solubility and a diminished SVE mass removal rate.

<sup>1</sup> Aerobic biodegradation rates can be found in Aronson et al. (1999) and Lawrence (2006).

- **Octanol-water partition coefficient ( $K_{ow}$ )** is the equilibrium ratio of the concentration of a compound in octanol to its concentration in water and is readily available from laboratory measurements.  $K_{ow}$  strongly correlates to the partitioning of a compound dissolved in water and adsorbed to the organic matter in soil solids (U.S. EPA, 1996d). With a higher partitioning coefficient, more of a compound is adsorbed to moist soil solids. This slows mass removal by SVE because the mass must dissolve into the water layer surrounding the soil particles and then volatilize into soil gas for removal.
- **Air and water diffusion coefficients** are used to estimate diffusion rates in soil gas (air) and soil moisture (water). Water diffusivities are orders of magnitude lower than air diffusivities, resulting in much slower diffusive transport through wet soil than dry.
- **Aerobic biodegradation rates** determine whether certain ancillary technologies that aerate the subsurface, like bioventing or air sparging, will increase contaminant removal by supplying oxygen to enhance biodegradation when used in conjunction with SVE. In general, petroleum hydrocarbons have high aerobic biodegradation rates and are amenable to these technologies while chlorinated VOCs do not aerobically biodegrade readily and are not effectively remediated by bioventing.

SVE as a soil treatment technology is effective for most VOCs and possibly effective for some semivolatile organic compounds depending on site characteristics and performance objectives such as a deadline to achieve remedial action objectives. SVE is considered ineffective for low volatility compounds such as polychlorinated biphenyls (PCBs), pesticides, dioxins/furans, cyanides, corrosives, metals, asbestos, radionuclides, and explosives. As described in Section 1, SVE is often applicable to fuel hydrocarbons, such as gasoline, that exist as an LNAPL. However, if chlorinated solvents are present as a DNAPL, SVE

alone is generally inadequate to address the mass because of the duration of operation.

## 2.2 Site Characteristics

Given a contaminant in soil with a volatility yielding an appreciable vapor concentration, the success of SVE generally depends on effective soil gas flow and contaminant mass transfer in the subsurface. The primary site properties governing soil gas (air) flow and contaminant transport are:

- Soil gas permeability
- Moisture content
- Organic carbon content of the soil
- Heterogeneity in the above properties.

Dry soil gas permeability can be related to soil grain size (Domenico and Schwartz, 1990) and native soil permeability can be estimated from laboratory tests on undisturbed soil cores; however, field extraction tests are directly applicable to SVE and yield bulk soil estimates of permeability. Air (soil gas) flow in the subsurface is generated by applying a vacuum to extraction wells screened in the contaminated soil. From Darcy's law, the extraction rate is proportional to the soil permeability to air flow and the applied vacuum (Johnson et al., 1990b). The total system extraction rate depends on the number of wells, the length of well screens, and, to a lesser extent, the well spacing. Johnson et al. (1990b) provide a simple expression for flow from a single well assuming a homogeneous, uniform soil permeability. Based on their work, the following engineering relationship can be used to estimate the maximum practical flow from a single well,  $Q$  (scfm), per unit length of screen,  $H$  (ft), or given measures of those parameters, an estimate of the absolute dry soil gas permeability,  $k$  (Darcy):

$$\frac{Q}{H} = \frac{\pi k k_r P_w [1 - (P_{atm}/P_w)^2]}{\mu \ln(R_w/R_i)}$$

This relationship includes the absolute pressure at the well,  $P_w$ , and the atmospheric pressure,  $P_{atm}$  (inches

of H<sub>2</sub>O), the ambient viscosity of air,  $\mu$  (g/cm/sec), the radius of the extraction well,  $R_w$  (ft), and an assumed radius of influence for the SVE vacuum,  $R_i$  (ft).

In this relationship,  $k_r$  is the unitless relative permeability. The relative permeability is a function of the fraction of pore space occupied by water, known as saturation,  $S$ . Higher water contents reduce the permeability to gas flow by occupying more pore space and reducing the air-filled porosity. The water saturation is readily available from straightforward measures of the soil total porosity and moisture content. Numerous correlations exist for relative permeability based on moisture content (as fractional saturation). The following common correlation is a modified Brooks-Corey relation (Brooks and Corey, 1964):

$$k_r = (1 - S)^3$$

When the water saturation is high (on the order of 70% to 80% of the pore space), the gas phase is mostly disconnected into bubbles and gas flow is orders of magnitude less than the flow through dry soil. Under these conditions, very little if any gas flow occurs under practical vacuums at the extraction well.

To utilize the above Johnson equation, the vacuum at the well is input as the absolute pressure at the well,  $P_w$ , assumed in this example to be 100 inches H<sub>2</sub>O less than the atmospheric pressure,  $P_{atm}$ , which is assumed to be standard pressure at sea level of 407.5 inches H<sub>2</sub>O. The expression also includes the ambient viscosity of air,  $\mu$ , at 0.00018 g/cm/sec. Values for  $R_w$  and  $R_i$  vary by well construction and site conditions but a typical well radius is 0.5 ft and an example radius of vacuum influence is 100 ft (Johnson et al., 1990b). Entering these values into the Johnson equation above yields:

$$\frac{Q}{H} \left[ \frac{\text{scfm}}{\text{ft}} \right] = k[\text{Darcy}] (1 - S)^3 (1.42)$$

For a fine sand with a permeability of 1.0 Darcy and a low porewater saturation of 0.15, we find  $Q/H$  is approximately 0.9 standard cubic feet per minute per foot (scfm/ft) while a medium sand of permeability 5.0 Darcy with a high water saturation of 0.5 yields the same rate. A high permeability sand of 10 Darcy with a low porewater saturation and a 20-ft screen yields 180 scfm. Consider a silt (0.1 Darcy) with a moderate saturation (0.4) to find a maximum flow of only 0.03 scfm/ft. For a 20-ft screen, the silt yields less than 1 scfm and would necessitate many closely spaced extraction wells to recover appreciable contaminant mass under conditions typical of a gasoline station. SVE alone may not be suitable in this last scenario. Contaminated vadose zones with high moisture contents also pose numerous process challenges for implementing SVE, including the generation of large quantities of wastewater and fouling of activated carbon.

For sites where appreciable gas flow can be generated, the contaminant mass extraction rate is governed by the transfer of mass from soil matrices to the flowing soil gas. The initial mass extraction rate can be estimated from measures or estimates of vapor concentration at the site multiplied by the anticipated total extraction rate. However, this rate diminishes over time, sometimes rapidly, as contaminant vapors in permeable pathways are swept out. This initial rate of diminishment is proportional to the contaminated soil volume and the extraction rate (i.e., the time required to sweep the contaminated vapor pore space) as discussed in Section 4.1.

After the initial decay in extracted concentration stabilizes, mass transfer constraints emerge that govern long-term trends and time to attain remedial action objectives. Mass transfer limitations exist on multiple scales, from pore-level partitioning between solid/liquid/gas phases to vapor diffusion on the scale of feet associated with geologic heterogeneity (e.g., permeability contrasts such as soil layering) and varying moisture content (Li and Brusseau, 2000).

Partitioning among phases on the pore scale is generally much faster than mass transfer constraints posed by geologic heterogeneities (Brusseau, 1991). Pore-level partitioning is generally assumed to be at equilibrium with chemical and soil properties defining the distribution of contaminant between the mass volatilized in vapor, mass dissolved in adjacent porewater, and mass adsorbed to soil solids. The soil properties include absolute (total) porosity ( $\phi$ ), water saturation ( $S$ ), bulk density ( $\rho_b$ ), and fraction of organic carbon ( $f_{oc}$ ). The chemical properties include Henry's constant ( $H$ ) and the octanol-water partition coefficient ( $K_{ow}$ ). The distribution coefficient  $K_d$  defines partitioning between porewater dissolution and soil solid adsorption and can be estimated using  $K_{ow}$  and soil fractional organic content ( $f_{oc}$ ). Henry's constant defines the partitioning between water and air.

The combined partitioning is represented by the vapor phase retardation coefficient ( $R$ ) common to contaminant transport modeling (Brusseau, 1991):

$$R = 1 + \frac{S}{H(1-S)} + \frac{\rho_b K_d}{\phi(1-S)H}$$

$$K_d = 0.6f_{oc}K_{ow}$$

Partitioning tends to retard the removal of contaminants by holding VOC mass in the porewater and soil solids as removal occurs in the vapor phase. Contaminants with a relatively high  $K_{ow}$  (e.g., xylene, perchloroethylene [PCE]) are extracted more slowly than those with a lower  $K_{ow}$  (e.g., benzene, trichloroethylene [TCE]) as high values suggest the compound more readily "sticks" to the solid. Similarly, compounds such as fuel oxygenates (e.g., MTBE) with a low Henry's constant tend to stay in the porewater rather than volatilize despite a high vapor pressure. As described later, transport modeling is often performed to assess cessation of SVE and site closure. This relationship illustrates the need to measure soil physical properties during site characterization efforts to ensure closure calculations

are as accurate as possible. Water saturation is of particular importance as it impacts flow through the higher relative permeability zones in a soil as well as retardation by dissolution into soil porewater.

Geologic heterogeneities impose mass transfer constraints that often dictate the duration of SVE operations. All sites have geologic heterogeneity, but it varies in degree. Even apparently uniform soils have variations in natural layering, clay and silt content, and moisture content, layers and lenses that are often imperceptible to the logging geologist but can be important for mass transfer. For example, consider an extensive silty clay lens holding a perched zone of water between two sand layers, and that this layered soil has been contaminated by leaks or spills infiltrating from the surface. For sites with interbedded sands and silts or clays such as this example, SVE induces flow through the sands that bypasses the silt and clay lenses because of their higher moisture contents and lower absolute permeability. In conceptual terms, the sands are advectively dominated (significant air flow) while the contaminated silts and clays are dominated by the much slower process of diffusion, where little if any gas flow occurs.

This phenomenon is illustrated in **Figure 2**, where contaminants are readily removed from more permeable soil layers by advection during the initial SVE period. Over time the extracted vapor concentration decays well below the concentration in less permeable soils, which then act as a source where the concentration gradient drives diffusive contaminant transport through the less permeable soil to the advective gas flow in the more permeable soil. The timescale for this diffusion process is proportional to the thickness of the silt/clay layer, that is, the distance over which diffusion must transport the contaminant to the flowing air. The soil moisture content again plays a key role by determining whether the diffusion is relatively fast (primarily through pore space occupied by air) or relatively slow (primarily through pore space occupied by water). Similar to the relative permeability, if a soil

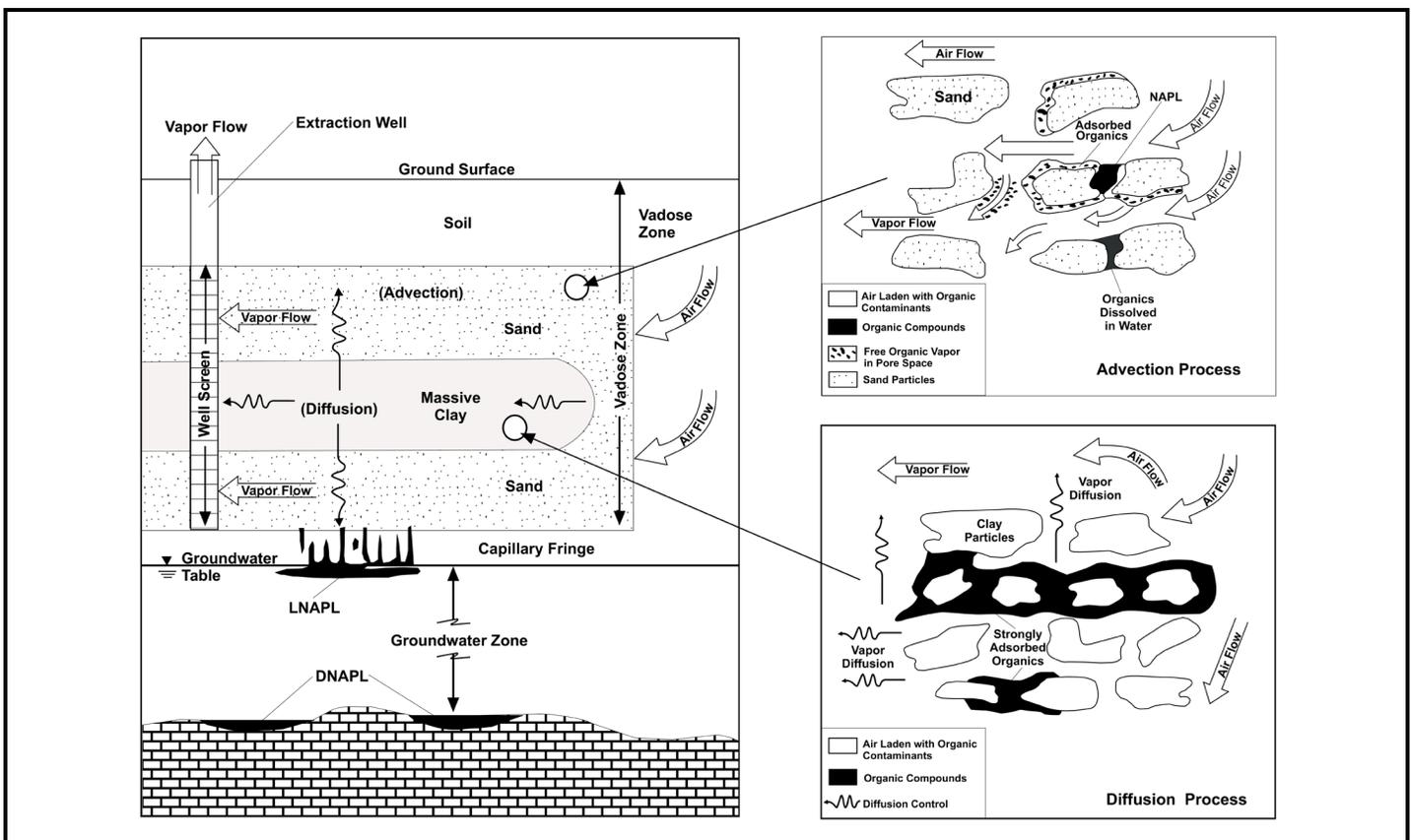
has a high water content and the air-filled pore space is disconnected and separated by lenses of water, the contaminant must diffuse through this water before it can be volatilized and extracted. The slow process of diffusion is the most common mass transfer constraint limiting cleanup at SVE sites where LNAPL or DNAPL does not exist. Consider again the example of the perched water lens; the extracted vapor concentrations may fall rapidly during initial SVE operations as contaminants are removed in soil gas from the more permeable zones, but once the SVE operations cease, contaminant vapor concentrations build slowly back to the initial condition by diffusion from the clay and water lens as only a small fraction of the initial contaminant mass was removed.

The timescale for diffusive transport (and mass transfer limitations) and the time to attain remediation goals can be approximated from mathematical models of contaminant transport. Such models are available

from the U.S. ACE (2002, Appendix F) and the U.S. EPA (2001, Chapter 13). The rate of vapor diffusion is governed by the retardation coefficient in the diffusive soil, the thickness of the fine-grained unit ( $Z_d$ ), the diffusion coefficient of the contaminant in free air ( $D_{air}$ ), the gas tortuosity of the soil ( $\tau$ ) (Jury et al., 1991), and the differential in the contaminant vapor concentrations as contaminants move from the diffusion-limited high moisture soil into the more permeable sandy soil where advective conditions predominate (U.S. ACE, 2002). An estimate for the optimal cleanup time,  $t_c$ , for a diffusive source can be calculated from the following equation, assuming the advective soil is kept at a very low concentration by the sweep of SVE (U.S. EPA, 2001):

$$\frac{C_{endpoint}}{C_{initial}} = \exp \left[ - \frac{\tau D_{air} \pi^2}{R Z_d^2} t_c \right]$$

$$Tortuosity, \tau = \phi^{1.3} (1 - S)^{3.3}$$



Source: After U.S. EPA, 1991b

Figure 2. Various mass transfer mechanisms during SVE

This relationship displays the exponential decay in concentration characteristic of long-term SVE and the tortuosity relationship illustrates the strong dependence of vapor diffusion on soil water saturation ( $S$ ). The thickness of the fine-grained soils harboring contaminants is clearly a dominant parameter. If the saturation is high, diffusion through water governs the process, and this diffusion will be about three orders of magnitude slower than diffusion through air. This makes SVE likely impractical but also contains the contaminant until the moisture content decreases. Rearranging the equation yields an expression for the optimal cleanup time given the initial concentration and a desired endpoint concentration:

$$t_c = \frac{RZ_d^2}{\tau D_{air}\pi^2} \ln\left(\frac{C_{initial}}{C_{endpoint}}\right)$$

As an example, assume sufficient flow is maintained to yield a low advective concentration (i.e., maximum concentration differential), a total porosity of 0.35, and a typical retardation coefficient for TCE of 3 along with a free air diffusion coefficient of 8 ft<sup>2</sup>/day. The time required is represented as:

$$t_c \sim \frac{0.15 Z_d^2}{(1-S)^{3.3}} \ln\left(\frac{C_{initial}}{C_{endpoint}}\right) \frac{\text{day}}{\text{ft}^2}$$

For a silt interval with a thickness of 3 ft and a water saturation of 0.60, we find the minimum timescale for cleanup effecting a reduction of two orders of magnitude in concentration within the silt to be on the order of 120 days, suggesting SVE will be effective. Whereas a thickness of 10 ft yields a best-case timescale exceeding 4 years despite best efforts to optimize operating conditions. Hence, sites with thick, moist silt or clay horizons in the vadose zone that have experienced decades of exposure to contaminants may not respond to SVE alone in a timely manner and are strong candidates for the application of enhancements such as heating or fracturing (U.S. EPA, 1997b).

**Figure 2** illustrates the removal of contaminant mass from the vadose zone above groundwater. At sites with contaminated groundwater, this water can also serve as a long-term source of vapors for extraction or volatilization and transport to the surface, a subject of interest for the mitigation of vapor intrusion. Determining the point of cessation for active SVE is complicated by the presence of contaminated groundwater: Will residual mass in the vadose zone impact groundwater in the future or will groundwater recontaminate the vadose zone negating much of the SVE effort and pose an unacceptable vapor intrusion risk? These questions are related to current EPA research efforts (Lutes et al., 2017; Schumacher et al., 2017; Truesdale et al., 2016) on the operational parameters and cost effectiveness of transitioning SVE systems from vadose zone cleanup to vapor intrusion mitigation. If contaminated groundwater is the primary source of contaminants for vapor intrusion, SVE has the potential to capture such vapors over a wide area, protecting multiple buildings on the scale of a city block with a minimal number of wells.

SVE is also applicable to LNAPL contamination, such as gasoline, that is amenable to aerobic biodegradation. Vapor extraction induces direct volatilization of the lighter-end components in LNAPL, and, thus, can be an optimal approach at sites with small to moderate levels of LNAPL because it simultaneously promotes contaminant removal and the introduction of oxygen for biological degradation. Sites with extensive masses of LNAPL would likely benefit from direct LNAPL recovery (e.g., dual-phase vacuum extraction along the groundwater smear zone) before considering SVE (U.S. EPA, 1997b). LNAPLs pose additional constraints on volatilization through the limited surface area between the LNAPL and flowing gas and the reduced vapor concentrations from a multicomponent LNAPL according to Raoult's law (Carroll et al., 2009).

These major subsurface conditions and contaminant attributes greatly affect the potential for SVE to be successful at a given site, although this list is certainly

not exhaustive (also see AFCEE, 2001; FRTR, 2008; MPCA, 1993). Additionally, it is important to note that SVE has been successful in suboptimal conditions, such as finer, wetter soils (e.g., clays), but at much slower removal rates (U.S. ACE, 2002).

### **2.3 Performance Objectives**

Regulatory compliance, exposure pathway risk, and post-cleanup site use (e.g., residential, commercial, industrial) generally lead to quantifiable goals for contaminant concentrations or fluxes and a desired attainment timeframe that are independent of remedial technology selection. These are usually documented in a Record of Decision (ROD) for Superfund sites or a Corrective Measure Decision at Resource Conservation and Recovery Act (RCRA)-regulated corrective action sites. If SVE is determined to be applicable and the goals are technically achievable, these goals provide the basis for SVE design, operation, optimization, transition, and closure. The order-of-magnitude calculations in Section 2.2 illustrate the first steps in setting the design basis.

The most common method for determining SVE site closure criteria in the past has been the assessment of potential aquifer degradation resulting from the transport of residual contaminants in the vadose zone to underlying groundwater. However, vapor intrusion into buildings has recently gained an equal footing for setting SVE site closure criteria. Both pathways are governed by the diffusive transport of vapors from a source in the vadose zone to an interface such as the foundation of an overlying building (for vapor intrusion) or the underlying water table surface (for the groundwater pathway). Mass transfer can be assessed across such interfaces to estimate the impact of the diffusive transport.

A typical remedial goal for the groundwater pathway requires that groundwater concentration meet a drinking water standard at a compliance location. Quantification of the VOC flux into the groundwater and subsequent calculation of estimated VOC concentrations in groundwater using a mixing

approach is one method to address this requirement. Similar flux calculations and mixing models can be applied to building basements or floor slabs to address the vapor intrusion pathway. Such methods are described by U.S. DOE (2013). Requirements to perform modeling based on these approaches can be reviewed before site characterization and SVE design to ensure that adequate data have been collected and to assess the likelihood of success in meeting remedial goals.

Assessing the rate of VOC mass removal by an SVE system is a closure approach often suggested by SVE operators. A strong desire arises to discontinue SVE when the VOC removal rate decays very slowly or approaches a perceived asymptote at low concentrations; however, this behavior alone is not a sufficient basis for termination. Asymptotic behavior is a supporting line of evidence for observations during rebound testing and for input to models assessing impacts to groundwater and vapor intrusion. This topic is discussed further in Section 6.

After a long application of SVE, significant VOC mass may remain in less permeable soils and concentrations may rebound after SVE is stopped. In such cases, removal can often be improved by altering the extraction strategy (e.g., operating different or new wells, transitioning to a lower extraction rate, pulsing SVE operation). Transitioning an SVE system from vadose zone cleanup to vapor intrusion mitigation is an area of active EPA research (Lutes et al., 2017; Schumacher et al., 2017, Truesdale et al., 2016). Sites deemed impractical for cleanup by SVE (e.g., DNAPL) can consider SVE for mitigation of vapor intrusion in lieu of subslab or basement systems. Design of systems for this objective follow the same procedures outlined in this EIP for vadose zone cleanup.

### 3 SITE CHARACTERIZATION AND CONCEPTUAL SITE MODEL DEVELOPMENT

The primary objective of site characterization is to inform the development and maintenance of a conceptual site model that includes information to design, install, operate, and evaluate an SVE system to meet performance objectives. This information can be expressed as the responses to several questions:

- What are the contaminants and in what phase (LNAPL or DNAPL or dissolved) were they released?
- What volume of soil is contaminated and where are the suspected source areas?
- What are the properties of the soil volume for transmitting soil gas? What fraction of the volume effectively transmits soil gas?
- Do major variations in permeability (e.g., soil layering) occur and if so, how thick and what are the physical properties of each layer? Are such intervals extensive across the site or are they limited lenses?
- What is the depth to groundwater? Do unusually high soil moisture contents occur anywhere in the vadose zone? Does the water table fluctuate seasonally or with changes in local water usage?
- Is the groundwater contaminated? What concentrations are found?
- What is the surface boundary condition? Is the contaminated soil volume under a building, parking lot, open field? Do preferential utility pathways or fill materials exist in the shallow subsurface?
- Where are potential receptors located and what are the current and future uses anticipated for the site? What are the expected endpoints and timeframes for the remediation based on the performance objectives?

The answers to these questions form the basis of a robust conceptual site model for the implementation of an SVE remedy at a VOC-contaminated site. As

with any conceptual site model, it can be continually refined as the SVE process moves through its various phases and additional information becomes available.

#### 3.1 Site Investigation

Data collected during all site investigation activities can be matched to one or more of the remedial objectives for the site. The scoping and applicability equations in Section 2 provide a template for the parameters to be measured and their specific purpose. For example, drilling and installing a single well can include the collection and analyses of soil cores from each soil type encountered while logging the thickness of differing stratigraphic intervals (or soil layers) in the well. These soil samples can be screened in the field for VOCs with handheld instruments, shipped to a geophysical laboratory for physical property analyses (e.g., porosity, moisture content), or shipped to an analytical laboratory for detailed chemical analyses. Drilling can also include the periodic collection of soil gas samples ahead of the drill depth to assess the vertical extent of contamination and a grab water sample if the boring extends into the groundwater. However, chemical analyses of very small samples of soil, water, and soil gas recovered from borings provide limited representativeness of the larger system. The location of this first and additional borings can be based on historical site usage, prior investigations, or new soil gas samples collected from temporary or permanent probes installed in the shallow vadose zone to better define the areal footprint of the vapor plume. These various investigative methods are described in detail in AFCEE (2001) and U.S. ACE (2002).

While the data described to this point are static in nature and reflect near equilibrium conditions, SVE is an active and dynamic process based on creating disequilibrium in concentration gradients. Hence, the site characterization can include steps to induce and measure disequilibrium early in the process before a full-scale system design is performed. For example, upon completing the first soil gas extraction well and a few soil gas sampling probes, the well can be used

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for short-term extraction tests to assess soil permeability, the response of subsurface VOC vapor concentrations during an initial sweep of permeable soils, and the rate of concentration rebound after this initial extraction. Such testing represents the initial SVE pilot test described below and in Section 4.1. Detailed descriptions of demonstrations combining site characterization with SVE pilot testing at multiple Air Force sites are available (Praxis, 2000).

### **3.2 Phased Approach**

Once the conceptual site model is sufficiently advanced to recognize the general nature and extent of VOC contamination, extraction testing can be conducted in a well near the suspected center of the source, or at least the center of the VOC vapor plume. The vapor plume will likely provide a cloud of contamination that masks the locations of much smaller source volumes. These can be uncovered by operating in pilot mode for a sufficient period to sweep a pore volume of soil gas from the initial plume volume while monitoring vapor concentration reductions (or increases) at surrounding soil gas monitoring points. SVE and bioventing system designers can collect site-specific venting performance data during this phase to support the design process. The pilot test can collect air permeability data from vacuum responses in monitoring probes (including subsurface probes if applicable) as well as VOC concentrations in soil gas to assess the radius of effective remediation from the single extraction well.

For permeable sites, vacuum responses may be low or undetectable in surrounding probes because of instrument limitations or variations in atmospheric pressure even though significant soil gas flow is occurring. In this case, monitoring of concentration responses is the most valuable metric for assessing radius of influence. This approach is also true of more distant soil gas probes at sites where lateral flow is dominant; vacuum response may be very low or undetected but concentration responses are observed.

Without such data, more wells than necessary might be installed and operated inefficiently.

For these reasons, beyond pilot testing, a phased approach to SVE system installation and operation has advantages over a single full-scale SVE design event. Much can be learned about the way a site behaves during remediation each time the operator goes to the field to collect data on system performance. However, these opportunities do require time and resources for which their judicious use balances against the extra expense and time of suboptimal operation. Because each new phase of the SVE remediation system is predicated upon the knowledge gained from the previous phases, design flexibility is essential because it accommodates design and operational changes as more information is gained about the site.

An initial remediation phase or a pilot test (discussed in Section 4) can further the understanding of the site and the applicability of SVE to remediate the site (U.S. ACE, 2002). In comparison to more traditional engineering projects (e.g., bridge design), the basis for design for subsurface environmental remediation is quite weak and often the very execution of a remediation design (e.g., installation of SVE injection and extraction wells) dramatically increases the understanding of site characteristics and confidence in the conceptual site model. Considerable time and expense can be saved if SVE is assumed to be the remedy for sites contaminated by VOCs in the vadose zone and the SVE is then designed and implemented using a phased approach. If SVE alone is found to be inadequate in an early phase, a robust conceptual site model is available to assess more aggressive technologies.

In a phased approach to design and implementation, site characterization and SVE pilot testing merge to facilitate deployment of cost-effective vapor treatment systems, minimize oversized equipment, minimize the number of wells operated (and therefore the number of “dead zones” between wells where remediation is inefficient), and identify and address

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persistent sources early in the process to reduce the remediation timeframe. The most efficient SVE system utilizes one extraction well in the center of the source volume, as long as it reduces the furthest lateral extent of the vapor plume of concern within the same timeframe as reductions in concentrations in the source volume. Consider the simultaneous startup of multiple extraction wells; the wells effecting changes at various locations cannot be discerned and dead zones, also known as stagnation zones, may provide false indicators of a persistent source volume only because flow is locally stagnant despite a substantial vacuum response.

The primary SVE design parameters are (1) the nature and extent of contamination in the soil, (2) the permeability distribution (i.e., heterogeneities) in the soil, and (3) contaminant concentrations in extracted soil gas. In historical practice, the nature and extent of contamination in the soil were determined with expensive chemical analyses of very small samples of soil, water, and soil gas recovered from exploratory borings. Because of their limited representativeness of the larger system, such results are not amenable to predicting SVE performance. Data representative of remediation conditions are needed to develop an appropriate design. In recent practice, field testing as described above is used to gather air permeability data and extracted VOC concentrations in soil gas. Many guidance documents (e.g., DePaoli et al., 1991; Johnson et al., 1990a, b; Pederson and Curtis, 1991) describe this test. However, the extraction testing has a deficiency because it does not account for the soil heterogeneities that control cleanup (Armstrong et al., 1994; McClellan and Gillham, 1990). Site characterization techniques to quantify the impact of heterogeneities on SVE can also be employed.

The U.S. Air Force conducted field demonstrations of advanced characterization tools for sites with soil layers of varying permeability (AFCEE, 2001). The tools included direct push with Geoprobe's membrane interface probe (MIP) technology and vertical profiling of extraction well screens using the PneuLog® technology. PneuLog provides

simultaneous, continuous logs of VOC concentrations and flow entering along an installed well screen. Interpretation of the data provides continuous vertical profiles of air permeability and adjacent soil gas concentrations. Logs from multiple operating SVE wells effectively define the extent of mass transfer limitations at a site. Additional information and descriptions of the MIP and PneuLog technologies can be found in Parsons (2001) and U.S. ACE (2002).

A second method to assess the mass transfer limitations in general, or in conjunction with the profiling tools, is to conduct the pilot test over a time sufficiently long enough to sweep the permeable soils and observe VOC concentration reductions in soil gas, and then observe the rebound in concentrations in soil gas probes once the SVE system is shut down. The rate of rebound and the reduction in the equilibrated rebound concentration provide valuable data for assessing the time of operation to achieve performance objectives as well as a benchmark for assessing progress toward cleanup during subsequent operations (Brusseau et al., 2010, 2015).

In summary, a phased approach to SVE system design and installation identifies and addresses persistent sources early in the process to allow course corrections and to reduce the remediation timeframe. Rapid reduction of a vapor plume may provide mitigation, but it does not necessarily indicate significant progress toward cleanup if the system is not extracting soil gas efficiently from low permeability areas, dead zones, or unknown sources where significant VOC mass may reside. With a phased approach, as the conceptual site model is refined and the SVE process moves forward, such problem areas in the subsurface can be identified early and subsequent efforts can be focused, including possible SVE enhancements described in Section 8.

## 4 DESIGN AND INSTALLATION

The implementation of SVE appears deceptively straightforward as only limited parameters form the basis for design of technology infrastructure:

- Total gas extraction rate,  $Q$
- Number and location of extraction well screens
- Vapor treatment technology for system off-gas.

The primary determinants for these SVE design parameters are the (1) nature and extent of contamination in the soil, (2) permeability distribution (i.e., heterogeneities) in the soil, and (3) contaminant concentrations in extracted soil gas. This information is expected to be available from an evolving conceptual site model as described in Section 3 and the pilot testing described in Section 4.1. As described in this section, a myriad of straightforward details arises in the design and implementation of SVE after specifying the vapor extraction rate and well designs and layout.

### 4.1 Pilot Testing and SVE Design Basis

Conventional site characterization data are important for evaluating SVE; however, these data are relatively static and do not provide adequate data for full-scale design. In particular, the dynamic behavior of the contaminant mass extraction rate is difficult to predict without performing a pilot test of SVE. The extraction behavior is governed largely by the volume of contaminated soil, the fractions of the soil volume characterized as advective versus diffusive, the mass transfer characteristics of the diffusion-limited source zones, the location of extraction screens relative to sources, and the existence of a NAPL. The following discussion does not consider a NAPL, although a zone of persistent concentration that returns to near identical equilibrium concentration after multiple periods of extraction is an indicator of NAPL.

The earlier pilot testing occurs in the remedial planning process (preferably as a component of site characterization), the less likely that design modifications will be needed after system startup.

Pilot testing is especially recommended at larger, more complex sites.

Designing the pilot test requires specifying a desirable total gas extraction rate or duration of extraction. Ideally, the pilot test will extract the equivalent of one or more (three in the example below) full pore volumes of soil gas from the contaminated soil. The purpose of this flushing is to operate the system long enough to observe the initial decay in the extracted VOC concentration and concentration reductions in soil gas probes at varying distances. This will provide a first estimate for mass transfer constraints and the radius of effective remediation from a single well (DiGiulio and Varahan, 2001a). As a rule of thumb, the rate and duration for the pilot test can be based on the total volume ( $V$ ) of contaminated soil in the conceptual site model, the soil porosity, and the soil moisture content as follows:

$$Qt = V_{soil}\phi(1 - S)$$

As an example, consider a small site with a total porosity ( $\phi$ ) of 0.35, a water saturation ( $S$ ) of 0.3, and a TCE-contaminated depth interval of 20 ft across a circular area with a radius of 50 ft. For these values, the minimum purge volume is:

$$Qt = \pi(20 \text{ ft})(50 \text{ ft})^2(0.35)(1 - 0.3) \\ \approx 40,000 \text{ ft}^3$$

Assume the pilot test is performed with a single phase, 120V blower capable of extracting 40 scfm. The duration of extraction to flush, or exchange, an equivalent pore volume is then:

$$\text{vapor pore volume exchange rate, } t \\ \approx \frac{40,000 \text{ ft}^3}{40 \text{ scfm}} = 1,000 \text{ min} \\ \approx 16 \text{ hours}$$

Hence, for the three pore-volume target, a 48-hour extraction test with vapor point concentration and vacuum monitoring, followed by a monitored rebound in concentration, would be desired. Consider

also that previous vapor sampling suggested a maximum TCE vapor concentration of 600 ppmv (3,300 mg/m<sup>3</sup>), yielding an initial TCE mass extraction rate of:

$$\begin{aligned} \text{initial mass extraction rate} \left[ \frac{\text{lbs}}{\text{hr}} \right] &= QC_a \\ &= (40 \text{ scfm}) \left( 3,300 \frac{\text{mg}}{\text{m}^3} \right) \\ &= 0.5 \frac{\text{lbs}}{\text{hr}} \end{aligned}$$

Assuming 200 lbs of granular activated carbon (capable of adsorbing 10% of its weight in TCE) is procured as a primary vapor treatment system (with a second drum for polishing before atmospheric discharge), a minimum extraction period of 40 hours is available (200 lbs x 0.1 / 0.5 lbs/hr). However, the concentration is expected to decay after the initial 16 hours of extraction, allowing for a longer period (e.g., up to 72 hours).

TCE vapor concentrations during 3 days of extraction at 40 scfm in a well placed near the center of a suspected source zone for TCE vapors are shown in **Figure 3**. The extracted concentration decayed rapidly during the initial hours of extraction in accordance with the estimated soil gas extraction and exchange rate. The TCE concentration then followed a much slower decay during subsequent extraction that is associated with diffusive mass transfer constraints in a confining clay unit in the middle of the vadose zone. These observations indicate that the pilot system was adequate to serve as the full-scale system at this small site. Use of activated carbon for off-gas vapor treatment was also demonstrated to be cost effective.

Note that the desired flow rate could be achieved with extraction through a single well only if the soil permeability satisfied the previously described flow relationship:

$$\frac{Q}{H} \left[ \frac{\text{scfm}}{\text{ft}} \right] = k[\text{Darcy}](1 - S)^3(1.42)$$

$$\begin{aligned} k[\text{Darcy}] &\geq \frac{40 \text{ scfm}}{(20 \text{ ft})(1 - 0.3)^3(1.42)} \\ &= 4 \text{ Darcy (a medium sand)} \end{aligned}$$

For lower soil permeability, a second well may have been required to achieve the desired flow or a longer flushing period may have been necessary to identify the mass transfer constraints. As described later, additional information on the mass transfer constraints was obtained by measuring the rebound in the TCE vapor concentration at the well after extraction ceased. In addition, if the TCE vapor concentration had been higher initially and persisted at a substantially higher value after the initial decay, suggesting the existence of a DNAPL, carbon adsorption may not have been cost effective for the higher mass extraction rate.

Monitoring points can also be installed at multiple depths, including subslab if applicable, and within the radius of influence range (e.g., 10–50 ft) of a pilot extraction well, if not already available from previous site characterization activities. Each monitoring location could have multiple nested points across the vertical extent of the vadose zone depending on the depth to groundwater and the geologic layering. As illustrated in **Figure 4**, points can be placed above, below, and within suspected sources. During pilot testing, these locations are used to measure both vapor concentration and vacuum responses.

The utility of vacuum data is highly dependent on the permeability of the soils and the data cannot be relied upon to assess the radius of influence for SVE. Of more importance is the vapor concentration response. In permeable sands, a very small vacuum response may be associated with a relatively high flow of air, whereas a significant vacuum response in a clay provides no evidence that appreciable flow is associated with the vacuum. However, the vacuum monitoring data can be used to assess the lateral versus vertical extent of flow and the impact of surface conditions (e.g., low permeability leakage across a slab or a soil surface open to atmosphere) on the flushing of the surface soil volumes.

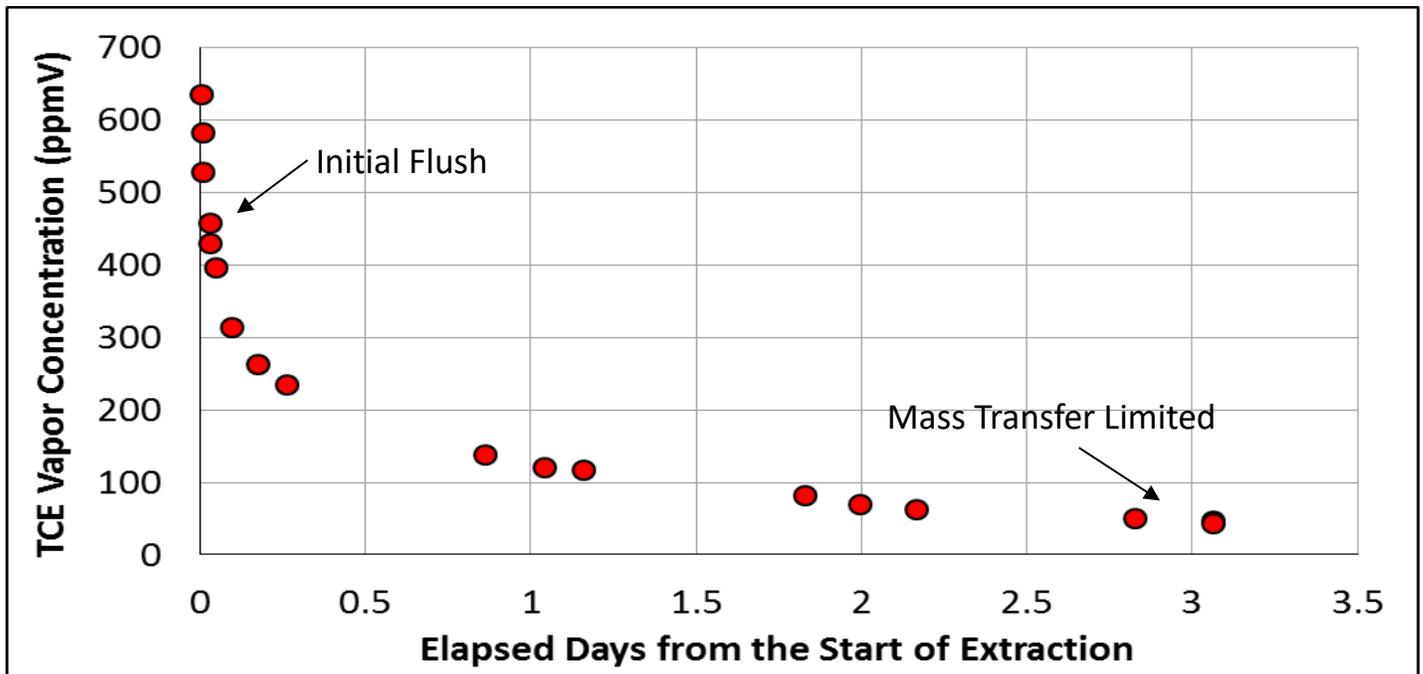


Figure 3. Example vapor concentration data from an SVE pilot test

During pilot testing, a robust monitoring program for VOC vapor concentration is recommended to identify trends in soil gas monitoring points. These trends can be correlated with the pore volume of soil swept during the pilot test to provide a basis for the spacing of extraction wells in the full-scale design based on the desired flushing frequency (i.e., pore volume exchange rate), as discussed in the next section. Use of a field gas chromatograph by an experienced operator is encouraged to cost effectively increase the size of the soil gas VOC dataset.

Often, the direct discharge of off-gasses without treatment is unacceptable because of health, safety, or public concerns. If conditions indicate it is necessary, off-gas treatment technologies such as activated carbon, thermal oxidization, or other relevant technologies can be implemented to improve the off-gas quality for release to the atmosphere (U.S. EPA, 2006).

#### 4.2 Total Soil Gas Extraction Rate

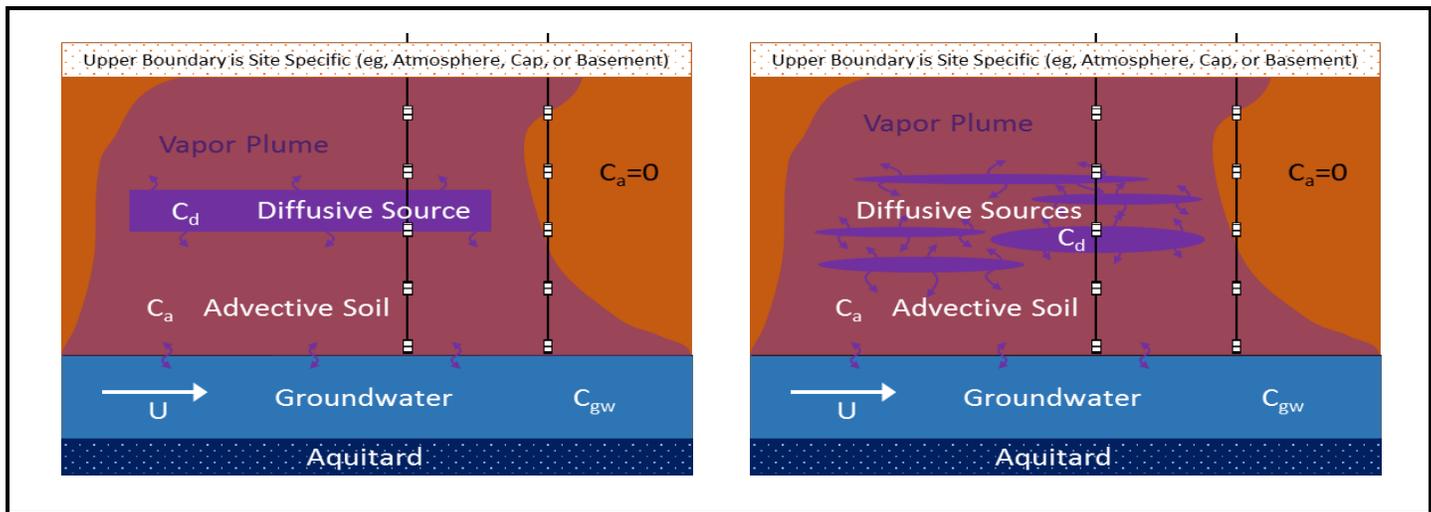
As illustrated in the pilot test example, the total soil gas extraction rate for design of an SVE system is related to the pore volume of the contaminated zone

and the exchange rate for that pore volume. The VOC-impacted pore volume is determined from the total volume of contaminated soil in the conceptual site model, the soil total porosity, and the soil moisture content. Conceptually, the pore volume exchange rate needs to be frequent enough to maintain a low extraction concentration relative to the source vapor concentration to optimize mass transfer from diffusive source zones to soil gas flowing through advective soils.

Recall the previous discussion of optimal timescale to attain cleanup in Section 2.2. This timescale is based on a characteristic time for contaminants to diffuse into permeable soils and be extracted with the soil gas. The time constant (or characteristic time) in the exponential decay for mass transfer provides a first estimate for the frequency of sweeping the soil pore volume to maintain a near maximum concentration gradient (U.S. ACE, 2002):

$$\text{timescale, } t_{diff} \sim \frac{RZ_d^2}{\phi^{1.3}(1-S)^{3.3}D_{air}\pi^2}$$

*Mass Transfer by Diffusion*



**Figure 4.** Conceptualized scenarios for diffusion-limited mass transfer and typical soil gas monitoring points

Using this timescale to define the pore volume exchange frequency yields the following estimate for the minimum total soil gas extraction rate to maintain a low extracted VOC vapor concentration and relatively high mass transfer rate:

*Flushing Timescale*  
 $\approx$  *Mass Transfer Timescale*

$$t = \frac{V_{soil}\varphi(1-S)}{Q} = \frac{RZ_d^2}{\varphi^{1.3}(1-S)^{3.3}D_{air}\pi^2}$$

$$Q = \frac{V_{soil}D_{air}}{Z_d^2R}\pi^2\varphi^{2.3}(1-S)^{4.3}$$

For typical soil and TCE properties ( $R = 3$ ), we find:

$$Q = \frac{V_{soil}}{Z_d^2}3\left(8\frac{ft^2}{day}\right)\pi^2(0.35)^{2.3}(1-0.3)^{4.3}$$

$$Q = \frac{V_{soil}}{Z_d^2}\left(0.00035\frac{ft^2}{min}\right)$$

Hence, knowledge of the characteristic thickness of contaminated fine-grained soil layers and the total soil volume in the source area provides the needed data for a first estimate of the design total soil gas extraction rate. Data from the site characterization, such as soil boring logs, or data from vertical profiling as described in Section 3.2 can be used for this estimate. For example, consider a relatively large site

covering one acre ( $43,500\text{ ft}^2$ ) with a vertical extent of contamination of 50 ft:

$$Q = \frac{1}{Z_d^2}\left(0.00035\frac{ft^2}{min} \times 43,500\text{ ft}^2 \times 50\text{ ft}\right) = \frac{767\text{ ft}^5}{Z_d^2\text{ min}}$$

If diffusion occurs over a depth interval of 3 ft, a minimum extraction rate of 85 scfm is specified. If mass transfer is limited by thick intervals, say 10 ft, a much lower extraction rate of only 8 scfm is required. The higher soil gas extraction rate is the result of faster mass transfer but yields faster cleanup. Conversely, the lower mass transfer yields a low extraction rate but attainment of remedial action objectives may be unacceptably long.

To be conservative, many SVE designs largely exceed these minimum rates and employ an off-gas vapor treatment system based on the initial contaminant mass extraction rate that rapidly become cost inefficient. Doubling the extraction rate beyond the rate matching mass transfer serves mostly to dilute the extracted concentration with only an insignificant increase in the mass extraction rate.

In more complex settings, such as the scenario in **Figure 4** depicting multiple small discrete sources, the diffusion length can vary significantly within the source zone. In the left sketch of the figure, a simple,

single, thick fine-grained interval governs the mass transfer, although the rate is expected to be slow and the interfacial area with flowing air is small. However, cleanup of the more complex scenario on the right will proceed faster for the same volume of contaminated soil and mass of contaminant because of the shorter diffusion lengths and increased interfacial area between the flowing gas and sources.

For the more complex scenario illustrated on the right, an alternative, more empirical approach is recommended. Fitting the concentration during extraction to a sum of exponential decays, representing the early sweep of the site and later mass transfer limited mass removal, yields an estimate for the site-averaged rate of mass transfer. These periods are illustrated in **Figure 5** and the fitting equation and procedures are described in Section 5, U.S. ACE guidance (2002, Appendix F), and U.S. DOE guidance (2013, Addendum to Appendix A). A detailed discussion of other similar design models is available in Nyer et al. (2001). **Figure 5** also illustrates

the reduction in equilibrated VOC concentration observed with each subsequent rebound period as source VOC mass is removed and allows an assessment in progress toward cleanup as described by Brusseau et al. (2010, 2015).

### 4.3 Well Layout and Screening

The layout and screening of extraction wells can be based on optimizing the exchange rate of the pore volume in the contaminated soil as described above. The radius of influence assessed from vacuum responses away from the extraction wells is a secondary consideration used to refine the well layout (DiGiulio and Varahan, 2001a). The objective of extraction well spacing is to create subsurface flow sufficient to maintain mass transfer near maximum rates throughout the contaminated soil volume. Hence, the number of wells required is based on the total soil gas extraction rate and the anticipated soil gas extraction rate from a single well. Single-well extraction is determined from pilot testing and

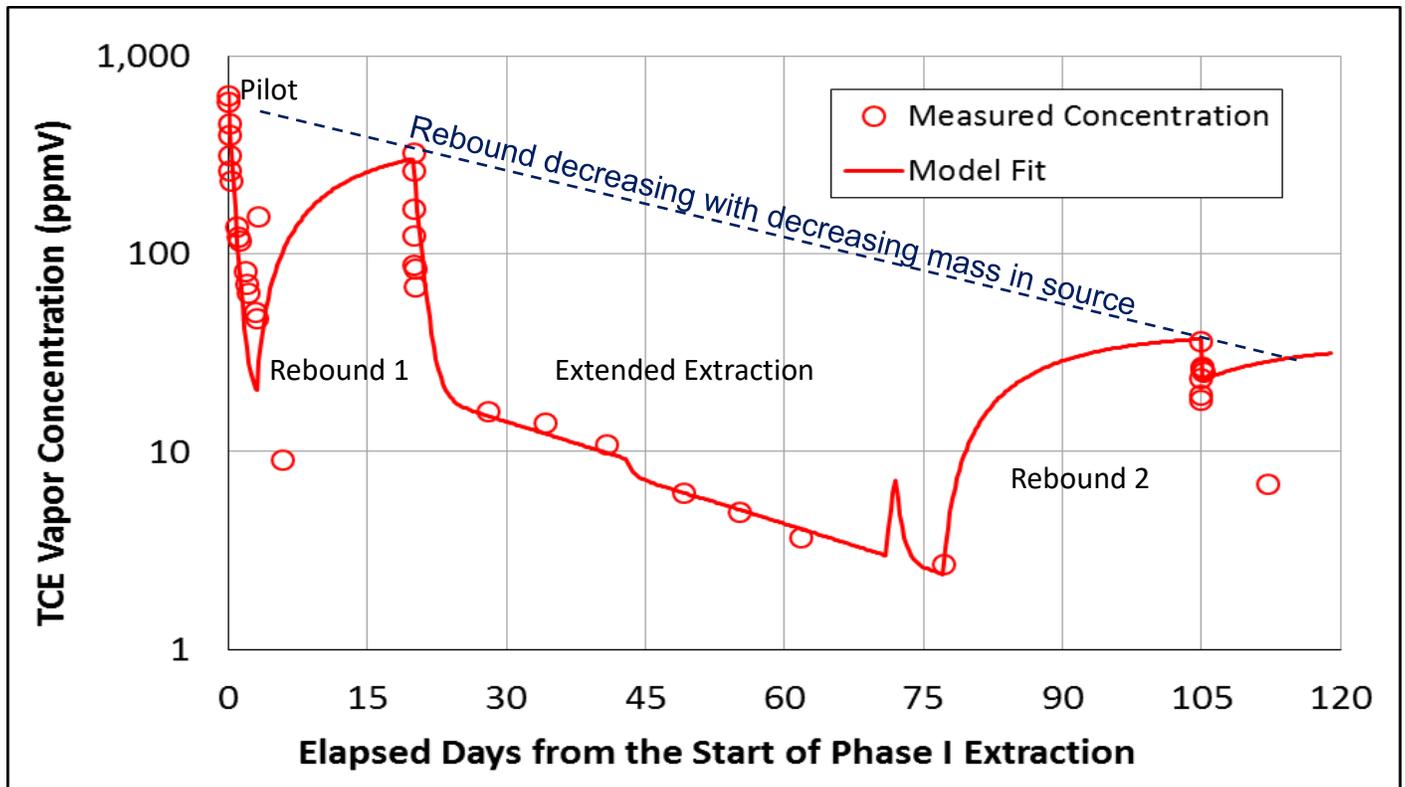


Figure 5. Parameter fit to SVE operations and periods of rebound

estimated from site permeability and the vacuum applied to the well screen. The minimum number of extraction wells (or screens) required is simply the total gas extraction rate divided by the flow per well (or screen). This number of wells and the spacing are refined based on the pilot test results, the locations of sources, and the necessity to rotate extraction among wells to mitigate the impact of stagnation zones between extraction wells. During pilot testing, vapor concentration monitoring is expected to identify zones of short-term response as compared to those with little response. A lack of concentration decay during the pilot test extraction has two likely causes.

First, if installed within permeable soils, the monitoring location is too distant from the extraction point and therefore beyond the radius of effective remediation. Second, if located close enough for locations, the extraction point is installed within a low permeability soil that will ultimately be associated with mass transfer constraints limiting the time of remediation.

The layout of wells is expected to be more closely spaced near the center of source zones and less dense toward the outer boundaries. As mentioned previously, the optimum SVE layout is a single well in the center of the contaminant source if the radius of effective remediation for that well is acceptable.

Other well design components include determining extraction well depth and screened interval, lateral extraction well placement and distribution, the use of nested wells, horizontal wells or existing wells, the use of vent wells (air injection wells), and well construction parameters, are more fully discussed in U.S. ACE (2002) and summarized below.

- **Nested wells:** At sites with a deep vadose zone and multiple lenses of contamination, a nested well design incorporating two or more wells in the same boring at different depth intervals may be ideal (e.g., a shallow, intermediate, and deep well nest would include three physically separate wells located within a few feet of each other vertically). Nested wells

are also recommended because of the pressure drop experienced along the well screen; for long screens, it is common for most gas flow to emerge near the top of the screen rendering the deeper portion of the screen ineffective.

- **Horizontal wells:** Horizontal vacuum extraction wells or trenches are effective at sites with shallow water tables, especially if surface seals are used to reduce short circuiting, or under surface infrastructure (e.g., buildings and roads). With a shallower depth to water, it is more likely that an extraction well screen will extend into the saturated zone and vacuum strength from the SVE system will cause additional water to rise further up the screen and create air blockage (Suthersan, 1999a). Additionally, if the vadose zone depth is less than 10 ft and the area of the site is quite large, a horizontal piping system or trenches may be more economical than conventional wells. Horizontal wells are also useful to reach VOC-contaminated soils under roads or occupied buildings.
- **Existing wells:** Existing monitoring or sparging wells can be used if they are screened properly and meet other system specification (e.g., well diameter, material compatibility).
- **Extraction well material:** Wells may be constructed of polyvinyl chloride (PVC) or stainless steel pipe with slotted PVC screen or stainless steel wire wrapped screen through the zone of contamination. PVC is cheaper and lighter to install than stainless steel. The choice of material should also consider compatibility with potential future enhancements (e.g., thermal remediation, in situ chemical oxidation).
- **Vacuum monitoring points:** If a monitoring well network is not already in place within the treatment area, an appropriate number and distribution of vacuum monitoring points will need to be installed. These points can be screened in the same vertical extent as the

extraction wells, with at least two wells being present within the treatment zone and four wells delineating the outside of the source area or treatment zone.

- **Air injection or air vent wells:** Some SVE systems are installed with air injection wells in expected dead zone areas within the active SVE area to minimize no flow zones. These wells may either passively take in atmospheric air or actively use forced air injection. Passive injection is unlikely to provide sufficient flow and, if rotation of extraction wells is insufficient to mitigate dead zones, active injection can be considered. However, the system should be designed so that the air injected into the system does not cause an escape of VOCs to the atmosphere. Proper design of the system can also prevent offsite contamination from entering the area being extracted (AFCEE, 2001; U.S. ACE, 2002).

Horizontal barriers to flow, such as surface covers and the water table, also can create dead zones. A detailed discussion on the operation of multiple extraction wells and the mitigation of dead zones is provided in Section 5.1. Additional well design information can be found in U.S. ACE (2002).

#### **4.4 System Sizing and Vapor Treatment**

Pilot testing results are highly useful for determining the total extraction rate, the applied vacuum required to achieve the flow rate, and the size and type of full-scale vapor treatment required. Oversizing vapor treatment for short-term pilot testing (e.g., doubling the estimated activated carbon requirement), as opposed to long-term full-scale operation, may be a good investment to avoid costly delays and multiple field mobilizations to complete the field testing. Many pilot tests fail to achieve the anticipated sweep of the contaminated soil volume because the off-gas vapor treatment system is exhausted prematurely (physically or financially). For example, if granular activated carbon (GAC) is employed for off-gas treatment, the quantity available for pilot testing should anticipate

initial concentrations remaining near maximum values until a full sweep of the active soil pore volume is completed rather than anticipating a rapid exponential decay of concentration. Full-scale design data will not be adequate when a pilot test is terminated before contaminant trends and mass transfer limitations can be observed. Once the desired total extraction rate, manifold vacuum, and trend for the initial vapor extraction concentration behavior are established, the blower type (e.g., variable frequency drive, positive displacement, regenerative) can be selected and a cost-benefit analysis performed to select a matching off-gas vapor treatment system as described in U.S. ACE (2002).

For off-gas treatment, activated carbon units are relatively cost effective and GAC is used frequently at low mass removal, diffusion-limited sites with VOC removal rates up to approximately 5 lbs/day. Activated carbon units usually require one-third of the maintenance required for thermal systems and are strongly preferred for chlorinated solvent sites. More options are available for petroleum hydrocarbon sites where extracted vapor concentrations are typically much higher than solvent sites. GAC adsorption capacity is based on VOC type, concentration, vapor temperature, and relative humidity. Water vapor sorbs to the GAC and leaves less capacity for the VOCs, and GAC capacity decreases with increasing temperature. Because the incoming air stream temperature can be elevated due to pumping and compression, there may be a need for off-gas cooling prior to GAC adsorption. Other types of air emission control devices used in SVE systems include catalytic and thermal oxidation, incineration, cavitation, photo-oxidation, ultraviolet oxidation, titanium dioxide, internal combustion, biofilters, and direct discharge. Additional information on air emission control devices for SVE systems can be found in U.S. EPA (2006).

## 4.5 Site Access, System Selection, Layout, Piping, and Instrumentation

Site access needs to be adequate to bring mobile drilling rigs onsite for construction of SVE wells and for trucks to deliver the equipment required for the SVE system (e.g., vacuum blowers, vapor-liquid separator, emission control devices, GAC canisters). SVE systems vary in size and complexity depending on the capacity of the system and the treatment requirements for vapor (off-gas) and liquid (produced water) effluents. SVE system components are typically transported by vehicles ranging from trucks to specifically adapted flatbed semitrailers; a proper staging area for such vehicles can be incorporated into design plans and plans for future site access for system modifications.

A small to medium commercial-size SVE system (e.g., 15 wells or less) requires about 100 ft<sup>2</sup> of ground area for the equipment skid and a height clearance of 10 ft. This area does not include space for the vapor treatment system, which is typically of similar area and height. Space may also be needed for a forklift truck to occasionally exchange skid-mounted GAC canisters when regeneration is required. Large systems with integrated vapor and liquid treatment systems will need extra area based on vendor-specific requirements. Power availability typically includes 3-phase 230 V or 3-phase 480 V, which meet the most common electrical service needs. For some SVE applications, water may be required at the site. The quantity of water needed is vendor- and site-specific (AFCEE, 2001; Nyer et al., 2001; U.S. ACE, 2002) but usually is small. Packaged SVE systems can reduce design and construction costs, but can be less effective if the system does not mesh well with site-specific characteristics.

Major system design considerations are highlighted in the following selection checklist by system component:

### Vacuum pump or blower equipment selection

- Use pilot test or modeling results to specify the wellhead vacuum at individual extraction wells

necessary to achieve the desired extraction rates.

- Perform detailed calculations for pressure drops through piping connecting extraction wells to the manifold entering the SVE vacuum pump or blower.
- Select a vacuum pump or blower sufficient to generate the vacuum at the manifold to achieve the desired extraction rates.
- For low vacuum and high flow, use regenerative blowers. For medium vacuum, use positive displacement blowers. For high vacuum resistance, use liquid ring pumps and install a dilution valve.
- Typical well vacuums range from 10 to 60 inches H<sub>2</sub>O.
- Higher air flow rates require larger equipment size and increased power, and higher operation and maintenance and emission control costs.
- At sites with a non-homogenous vadose zone, higher airflow rates may not remediate the site more quickly.

### Air/water separator and air filter

- Soil gas extracted by the SVE wells first enters an air/water separator to remove moisture, followed by an air filter to remove particulates, and then are usually pumped to the air treatment system.
- Moisture and particulate removal devices protect system equipment.

### Off-gas treatment technology

- Use pilot test data to determine whether the SVE system will likely exceed the Clean Air Act (CAA) thresholds for air treatment.
- Determine whether an air treatment system will be required or selected based on best management practices.
- Carbon adsorption using GAC is the most frequently implemented technology, especially for smaller sites with lower VOC concentrations.

- Conduct a cost analysis to consider all options.
- At sites with higher levels of contamination, larger scale equipment or more than one technology may be necessary.

#### **Flow, vacuum, and concentration measurement devices**

- Install flow, vacuum, and concentration measurement devices in the appropriate locations to monitor that the system is operating correctly and evaluate its overall effectiveness over different temporal scales.

#### **Piping**

- High density polyethylene (HDPE) is recommended for subgrade conveyance piping. It is easy to install, as it comes in large spools that can be rolled out along the trenches. It can be “swept” to make turns and bends, which avoids the use of elbows that create frictional losses. HDPE is also fuse welded rather than using glued fittings that tend to crack or break subgrade due to temperature fluctuations.
- Schedule 80 PVC can be used for above-grade piping on the vacuum side of the extraction blower. It is ideal for the manifold as cutting and gluing PVC pipe and fittings is generally much faster than assembling threaded steel pipe and fittings
- Blowers generally heat the air to a temperature greater than PVC can withstand, therefore metal pipe should be used for the discharge side of the blower. Generally, carbon steel or aluminum can be used, but the metal should be compatible with the constituents in the discharged air stream.
- Piping to extraction wells should include sumps or similar features to remove water from the piping, especially at low spots where water can accumulate and restrict air flow.
- Make sure to test underground piping for vacuum, pressure, and heat resistance prior to implementation.

#### **Sensory considerations**

- In population-dense areas, minimize noise by placing SVE equipment in a better soundproof building and consider visual appeal when selecting equipment or housing that will be viewable by the public.
- Oversized equipment is likely to result in excessive noise.
- Heat exchangers can be noisy, so allow for hot weather operation when evaluating noise impacts.

#### **4.6 Health and Safety Issues**

Given the uncertainties and potential exposure to explosive or toxic vapors, it is critical to define and address health and safety issues, along with regulatory concerns and objectives, prior to implementing and operating an SVE system. VOC contaminants typically present in SVE off-gases are usually hazardous because of their toxicity, ignitability, or other reasons (U.S. ACE, 2002). Therefore, practices such as proper selection of equipment components, monitoring of system off-gas, and evaluating what off-gas treatment is needed should be done early to ensure safety of personnel and the facilities.

Blowers and other electrical motor driven equipment (including wiring) must be designed and constructed in accordance with applicable National Fire Protection Association (NFPA) code, with proper consideration given to environmental conditions such as moisture, dirt, corrosive agents, and hazardous area classification. Hazardous area classification should follow practices outlined in the applicable NFPA code, and taking into consideration process equipment in the area, characteristics of hazardous liquids/gases, the amount of ventilation in the area, and the presence of equipment such as piping with valves, fittings, flanges, or meters. The classification of the area will determine the potential need for explosion-proof motors or other system components (U.S. ACE, 2002).

Monitoring of system off-gases may be conducted using multiple approaches to evaluate the potential

exposure for explosive or toxic vapor risks, as well as permit requirements for CAA rules. Monitoring may be conducted using an explosimeter (or combustible gas indicator) or appropriate VOC monitoring equipment, such as a flame or photoionization detector, as well as intermittent sample collection and analysis for specific VOC compounds of concern (U.S. ACE, 2002). When using on-site monitoring equipment, care should be taken to ensure that equipment is properly calibrated and all operating instructions and potential limitations as indicated by the manufacturer are understood. Sampling and laboratory analysis of system off-gases can also aid in determining contaminant levels for safety and regulatory (permitting) purposes.

## 5 OPERATIONS, MONITORING, AND PERFORMANCE EVALUATION

The design parameters developed during site characterization and pilot testing form the initial conceptual site model for evaluating SVE performance. This model evolves and is refined as field operations progress and more data become available. In particular, depending upon the range and frequency of monitoring and data collection, persistent sources that govern attainment of remedial goals become increasingly visible.

At the start of operations, a “cloud” of somewhat uniform contaminant vapors usually envelops the contaminated soil volume. Referring to **Figure 4**, this cloud hides the sources (i.e., the primary accumulations of contaminant mass resulting from the release) because most of the soil gas monitoring points in the figure would initially yield soil gas with high VOC concentrations.

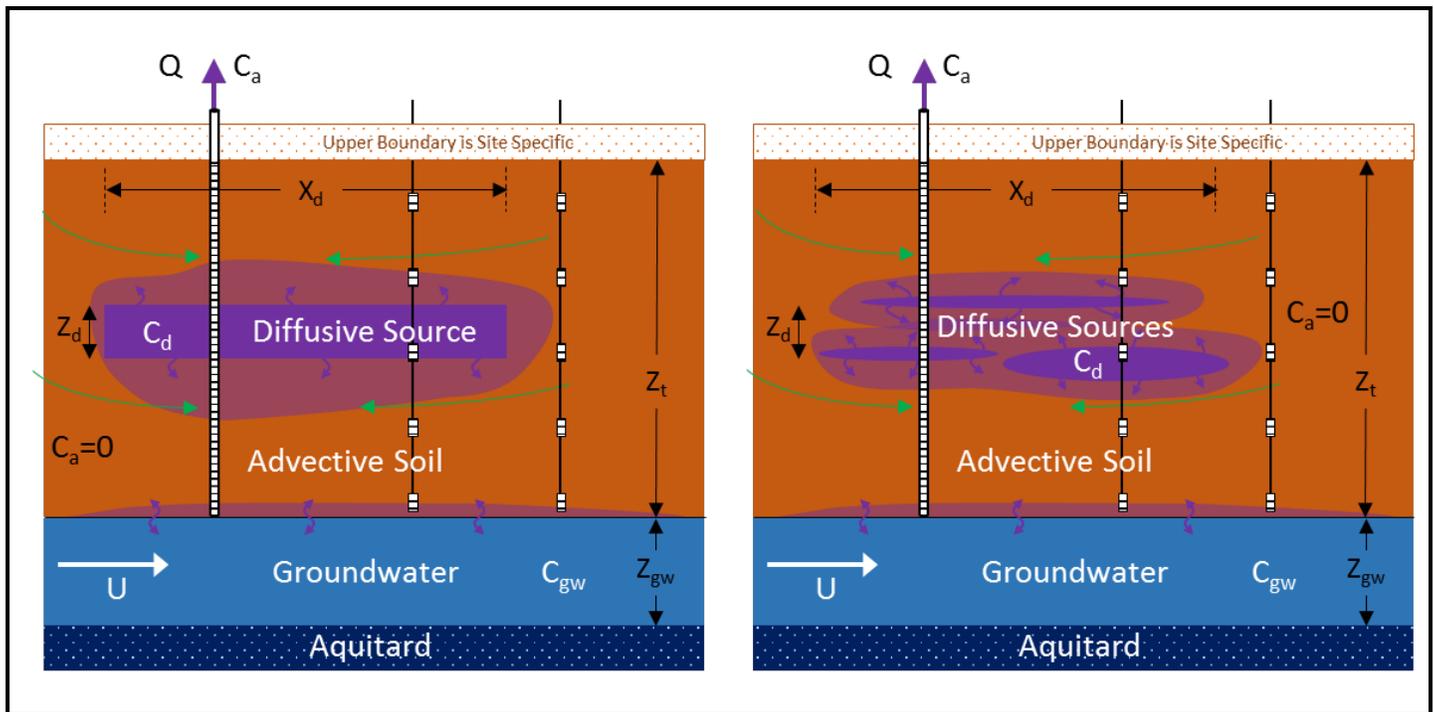
With the new dataset from the start of SVE, a review of geologic logs may substantiate observations about source areas (e.g., identification of a thin slit or clay layer considered unimportant before startup). As the high-concentration cloud is swept away by initial SVE operation, the locations of sources become better defined as illustrated in **Figure 6** where only the

monitoring points within or near the source lack a significant concentration decay. **Figure 6** also shows two scenarios for persistent sources that may yield nearly identical initial concentration decays in the monitoring points, as most practical monitoring networks are relatively sparse.

As described in this section, analysis of changes in the mass extraction rate over time and vapor concentrations during periods of rebound provide data for differentiating and characterizing the VOC sources. In this manner, SVE provides a wealth of data to generate a more accurate site model of contaminant transport that is directly applicable to assessing closure of a site. The physics of mass transfer during SVE are identical to those of transport during ambient conditions, when the vacuum-induced flow through the vadose zone is not present. Hence, the SVE mass extraction rate provides a worst-case estimate for a site-averaged contaminant mass flux toward the surface for vapor intrusion or downward mass flux entering groundwater. However, as discussed in this section, inefficient operation of multiple extraction wells or the existence of vertical barriers can complicate such assessments.

### 5.1 Operations and Monitoring

Details for operating, maintaining, and monitoring SVE systems are available from numerous guidance documents (e.g., U.S. ACE, 2002). Beyond maintaining and troubleshooting vapor extraction and treatment system operation (e.g., troubleshooting a frequent shutdown of a thermal oxidizer), a common operating issue is the production of water from vapor extraction wells. Water that collects in vapor conveyance piping can restrict flow from the subsurface and the introduction of water to a vapor treatment system reduces treatment efficiency. This problem tends to be seasonal, occurring with rain and cold weather (an opportune time to schedule rebound evaluations). Planning for the production of water and being prepared to predict and handle the excess water increases the efficiency of the SVE operation.



**Figure 6.** Conceptualized scenarios for diffusion-limited mass transfer during SVE

As described in Section 4.5, the piping to extraction wells should include sumps or similar access for removing water from the piping. Piping in a trench, for example, under a road, provides a low spot for the accumulation of water that must be removed through a sump to prevent the severe restriction of gas flow in the piping.

Other waste streams generated by SVE include those from VOC vapor treatment (e.g., spent GAC), wastewater produced from the SVE system, and potentially soil cuttings and personal protective equipment. Compared to ex situ treatment technologies and other soil remedies such as soil excavation, SVE systems generally produce less waste (U.S. EPA, 2010).

Standard remedial system monitoring for SVE includes temporal logging of the following parameters:

- Vacuum/pressure in monitoring and extraction wells
- Gas flow rate in extraction wells and manifolds
- VOC concentrations in monitoring and extraction wells (field instruments such as

photoionization detectors, flame ionization detectors, portable gas chromatographs; fixed laboratory analyses)

- Vapor treatment system compliance data (flow, destruction/reduction efficiency)
- Utility usage
- Water levels in the knockout tank
- Waste quantities for disposal
- Recordkeeping of system data and a log of SVE on/off times
- Recordkeeping of system maintenance (e.g., oil changes, water transfer from knockout tank).

Frequency of sampling VOC concentrations using field measurements can range from regular site visits (e.g., weekly) to a continuous data logger that electronically reports soil gas flow and VOC concentration measurements to a remote remedial technician. VOC samples are typically collected for laboratory analysis monthly to satisfy permit vapor treatment requirements although such sampling can be extended to individual wells or monitoring points of interest for correlating field instrumentation readings. Total mass of contaminants removed by the

SVE system can be calculated by multiplying the flow rate by VOC concentrations over time. The trends in mass removal from the site and individual wells are primary components of both system optimization and site closeout.

VOC concentrations at monitoring points are also typically measured by sampling and fixed laboratory analysis at least quarterly. The sampling program can include monitoring points located within the source zone and outside of the contaminated area (perimeter of compliance wells). Depending on the vertical extent of the plume, soil gas monitoring points may be located at different depths in well “nests” (AFCEE, 2001; Matzke et al., 2010; Suthersan, 1999a).

## 5.2 Data Evaluation

Common SVE operation practice is to generate a monthly or quarterly report from operating and monitoring activities that includes system operating time, maintenance performed, operational problems encountered and solutions, ongoing operational issues, data collected and graphed as a function of time, periodic and cumulative masses removed, and plans for the next reporting period. Assessments of progress toward cleanup goals can be made annually or as needed, and can be general statements until VOC concentrations are near or below a predetermined cleanup threshold or appear to plateau at levels well above a threshold. A straightforward, ongoing data evaluation that refines the conceptual site model and ultimately serves to support SVE cessation and site closure is ideal. Such data evaluations can be included in a progress report (as appropriate) and can include a “forecast” of system performance for the next reporting period to help identify anomalies or deviations from the conceptual site model that may require attention.

Observed trends in extracted soil gas VOC concentrations, monitored soil gas VOC concentrations, and VOC mass removal can be evaluated on a site-averaged scale by comparing the trends with anticipated trends representative of

subsurface conditions. For example, extracted soil gas VOC concentrations that plateau at elevated levels would be consistent with the existence of a layer of gasoline floating on the water table below the vadose zone, as other site data may suggest. Comparing these concentrations with equilibrium concentrations (i.e., VOC concentrations just above gasoline) also provides a rough estimate for the extraction “efficiency” governed by mass transfer between the fuel and flowing air. A detailed discussion of such a scenario and its evaluation are provided by Johnson et al. (1990a). SVE can also cause compositional changes in a petroleum product as a result of preferential volatilization, as described by Carroll et al. (2013).

For SVE at chlorinated solvent sites, the most common mass transfer constraint is between permeable soils where air flows (advective soils) and adjacent lesser permeable soils (diffusive soils) that hold contaminants dissolved in the porewater (see **Figure 6**). The mass transfer limitations of diffusive soils do not appear until the initial sweep of permeable, advective soils is complete. In its simplest form, this mass transfer limitation can be modeled by a bulk mass transfer coefficient,  $\alpha_d$  (Goltz and Oxley, 1994), averaged over the volume of the source zone:

$$R_d \frac{dC_d}{dt} = -\alpha_d(C_d - C_a)$$

Use of the bulk mass transfer coefficient is a simplistic method to quantify the physics of diffusion in the source zone. The first order estimate for the cleanup time provided in Section 2 is based on linear diffusion and the same physics yield a first order estimate for the mass transfer coefficient based on the same parameters (U.S. ACE, 2002; U.S. EPA, 2001):

$$\alpha_d \approx \frac{\tau_d D_{air} \pi^2}{R_d Z_d^2}$$

The impact of mass transfer on the extracted concentration,  $C_a$ , equivalent to a well-mixed average concentration in the advective soils, is described by U.S. ACE (2002, Appendix F),

$$R_a \frac{dC_a}{dt} = - \frac{Q}{V_{soil}\phi(1-S)f_a} C_a + \alpha_d \left( \frac{f_d}{f_a} \right) (C_d - C_a)$$

The site-averaged vapor concentration in the source (diffusive) soil is represented by  $C_d$ . The first term on the right describes the sweep of advective soils while the second term describes mass transfer contributions from the source soils. The retardation coefficient and other parameters are as defined previously. Note this simplistic representation of the vadose zone soils requires specifying the soil volume as either advective or diffusive expressed as a fraction of one ( $f_a + f_d = 1$ ). Geologic profiles or other vertical logging techniques such as PneuLog can be used to estimate the fractions.

In practice, an apparently uniform site likely has a maximum advective fraction of roughly 0.8 as moisture content varies. For a predominantly low permeability site, the advective fraction may be only 0.1 or 0.2 and SVE may not be applicable or will require years of operation. Given initial vapor concentrations for the soils roughly equal to the peak vapor concentration at the start of SVE ( $C_{d,0} \approx C_{a,0} = C_0$ ), a simple solution to describe the mass transfer limited behavior during extraction that is provided in U.S. ACE (2002, Appendix F). The solution is easily fit to field data to forecast future SVE performance and track progress. During the initial extraction period, mass transfer provides little contribution until the extracted concentration decreases significantly as the advective soil volume is swept. For this initial extraction period, the extraction concentration is approximately:

$$C_{a,initial} = C_0 \exp \left[ - \frac{Qt}{V_{soil}\phi(1-S)f_a R_a} \right]$$

Fitting extracted concentration data with this expression using measured concentrations, flow rate, and soil properties provides an estimate for the volume of advective soil ( $f_a V_{soil}$ ). At later times, the

extracted concentration changes very slowly and can be maintained much less than the average diffusive source concentration. Under this assumption, the diffusive concentration is approximately (Goltz and Oxley, 1994):

$$C_{d,late} = C_0 \exp \left[ - \frac{\alpha_d t}{R_d} \right]$$

After substituting this expression, solving the governing equation yields for later, diffusion-limited conditions is approximately:

$$C_{a,late} = C_0 \alpha_d \left[ \frac{V_{soil}\phi(1-S)(1-f_a)}{Q} \right] \exp \left[ - \frac{\alpha_d t}{R_d} \right]$$

Consider again the typical concentration decay presented in **Figure 3** for an SVE pilot test. Fitting this expression to the later VOC mass transfer-limited mass extraction provides an estimate for the bulk VOC mass transfer coefficient,  $\alpha_d$ , given measures for the soil properties and an advective soil volume estimate from the initial extraction period. As shown in **Figure 7** plotting the data on a log-log scale displays both the initial and later exponential behavior in concentration.

As illustrated in **Figure 7**, SVE extraction concentrations can be used to estimate site conditions relevant to the conceptual site model. In general, the procedure involves the following steps:

1. Estimate the volume of advective soil impacted by the contaminant source from the initial concentration decay; the extraction rate is measured and soil properties may be available from the site characterization.
2. Estimate the volumetric mass transfer coefficient from diffusive (source) soils to advective soil from the later exponential decay given the estimate of impacted soil from the initial decay. This step also requires a refined estimate of the fractions of soil characterized as advective and diffusive.

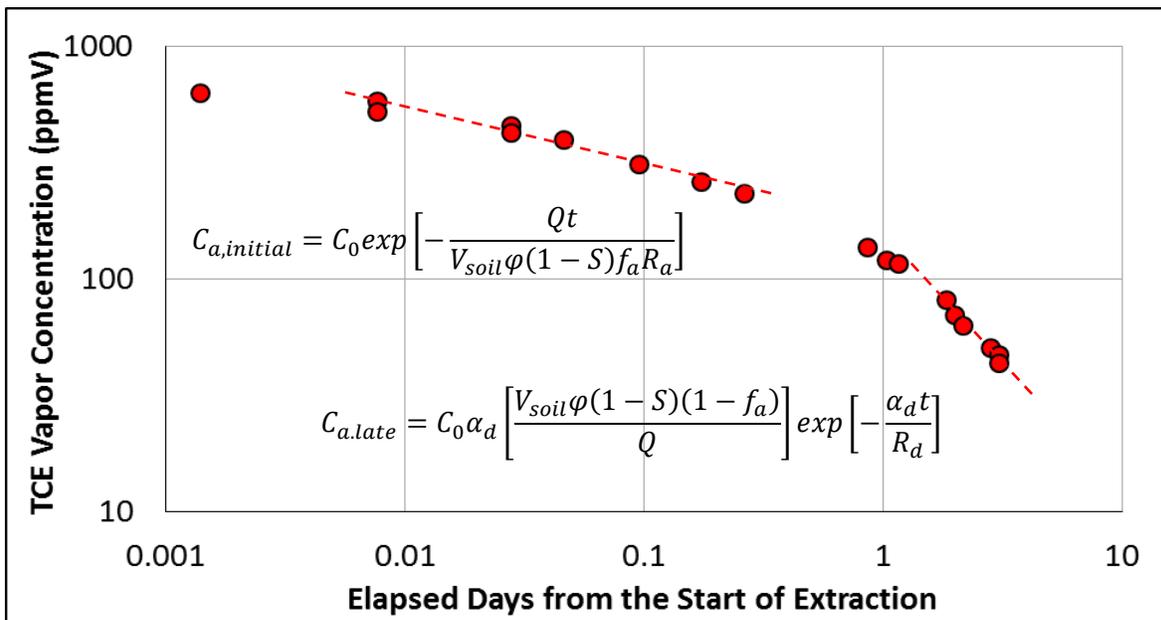


Figure 7. Conceptualized parameter fit to characterize SVE

3. Compare the estimates of total soil volume, fraction characterized as advective, and mass transfer coefficient with other site data such as vapor monitoring well data and geologic logs.
4. Refine the parameter estimates each reporting period and forecast results for the next period.
5. As described in U.S. ACE (2002), these parameter fits can be extended to include mass removal estimates and thereby residual mass estimates to track progress toward cleanup, optimize vapor treatment, and forecast timeframes needed to attain cleanup goals.

As the cleanup progresses, additional sources of VOC mass may appear on even slower timeframes. For example, a clay interval contributing to the extracted mass may only become discernable very late in the operation and through identification by individual monitoring points.

Another potential source of VOC mass is underlying contaminated groundwater. As SVE cleanup of the vadose zone progresses, VOC-contaminated groundwater starts to produce contaminant mass because of the disequilibrium according to Henry's law (vapor concentration equals water concentration multiplied by Henry's constant,  $H$ ). As vapor concentrations in the vadose zone decrease in

response to SVE, this equilibrium relationship drives VOC mass from the capillary fringe and groundwater into the VOC-depleted soil gas above the water table.

The transfer of VOC mass from groundwater to soil gas in the vadose zone is expected to be slow as the contaminant must diffuse from the water table through water in the tension-saturated capillary fringe to reach the air-filled pore spaces in the vadose zone. The transfer can be somewhat enhanced by a fluctuating water table that moves contaminated water up and then leaves a portion exposed to air-filled soil pore spaces when it retreats. The complex mass transfer from groundwater to the vadose zone and vice versa has been the subject of research for decades but with very little predictive capability for the practicing engineer (McCarthy and Johnson, 1993; U.S. DOE, 2013). The inclusion of contaminated groundwater as a source of VOC mass for SVE is relatively straightforward to add to the simple model presented above:

$$R_a \frac{dC_a}{dt} = -\frac{Q}{V_{soil}\phi(1-S)f_a} C_a + \alpha_d \left(\frac{f_d}{f_a}\right) (C_d - C_a) + \alpha_{gw}(HC_{gw} - C_a)$$

The VOC mass transfer coefficient at the water table interface between the bottom of the vadose zone and water table surface is difficult to predict but can be estimated near the end of SVE operations when contaminated groundwater becomes the primary source of VOC mass and is a potential source for vapor intrusion after SVE ceases. This topic is explored in Appendix B of this paper.

### 5.3 System Optimization

AFCEE (2001) recommends review of SVE operations from three perspectives:

- Evaluation and optimization of the operation of the existing system with the goal of maximizing the rate of contaminant mass removal to achieve the greatest reductions in contaminant concentrations and to minimize operating costs.
- Re-evaluation of the system components (e.g., wells, blowers, off-gas treatment system) to determine if changing or adding to the system will improve performance or to determine whether a wholly new technology is necessary.
- Re-examination of the remedial goals in light of new regulations, risk thresholds, or changes in exposure scenarios.

With respect to maximizing the rate of contaminant mass removal, the guiding principle is to extract soil gas as close as possible to the center of remaining sources of mass with the fewest number of extraction wells that site conditions will allow. This method minimizes stagnation zones and the introduction of dilution air.

When operating multiple extraction wells, the operating wells may be rotated to assess the impact of stagnation zones and source locations. A common misstep in attempting to optimize the configuration of extraction wells is to rotate wells too often, before the site has re-equilibrated to the changes in flow. The re-equilibration time is, at a minimum, a single pore volume exchange rate that may span days to weeks, negating the utility of measuring changes over hours

or a few days. A legitimate reason to add or subtract one or two extraction wells on a monthly or quarterly basis is to address the potential of a stagnation zone overlapping a source zone and prolonging remediation. Extraction wells close to a source zone shown to be near cleanup goals can be turned off to focus flow on more persistent source zones and to evaluate rebound effects. However, the potential for stagnation zones when operating multiple extraction wells requires detailed evaluation to assess whether a persistent concentration is the result of stagnation rather than a diffusive source. Plots of contaminant mass extraction rates from individual wells over time and application of the site-wide two-region mass transfer model described above can help identify the benefits or inefficiencies of various combinations of the extraction wells.

Stagnation zones are readily calculated from potential flow models, identical to those used to calculate capture zones in groundwater with zero groundwater velocity. Consider a system of three extraction wells, screened over identical depth intervals (**Figure 8**). When all three wells are operated, two stagnation zones exist at the elevation of the extraction screens as indicated on the left-hand side of the figure where the blue lines represent streamlines of air flow toward the extraction wells.

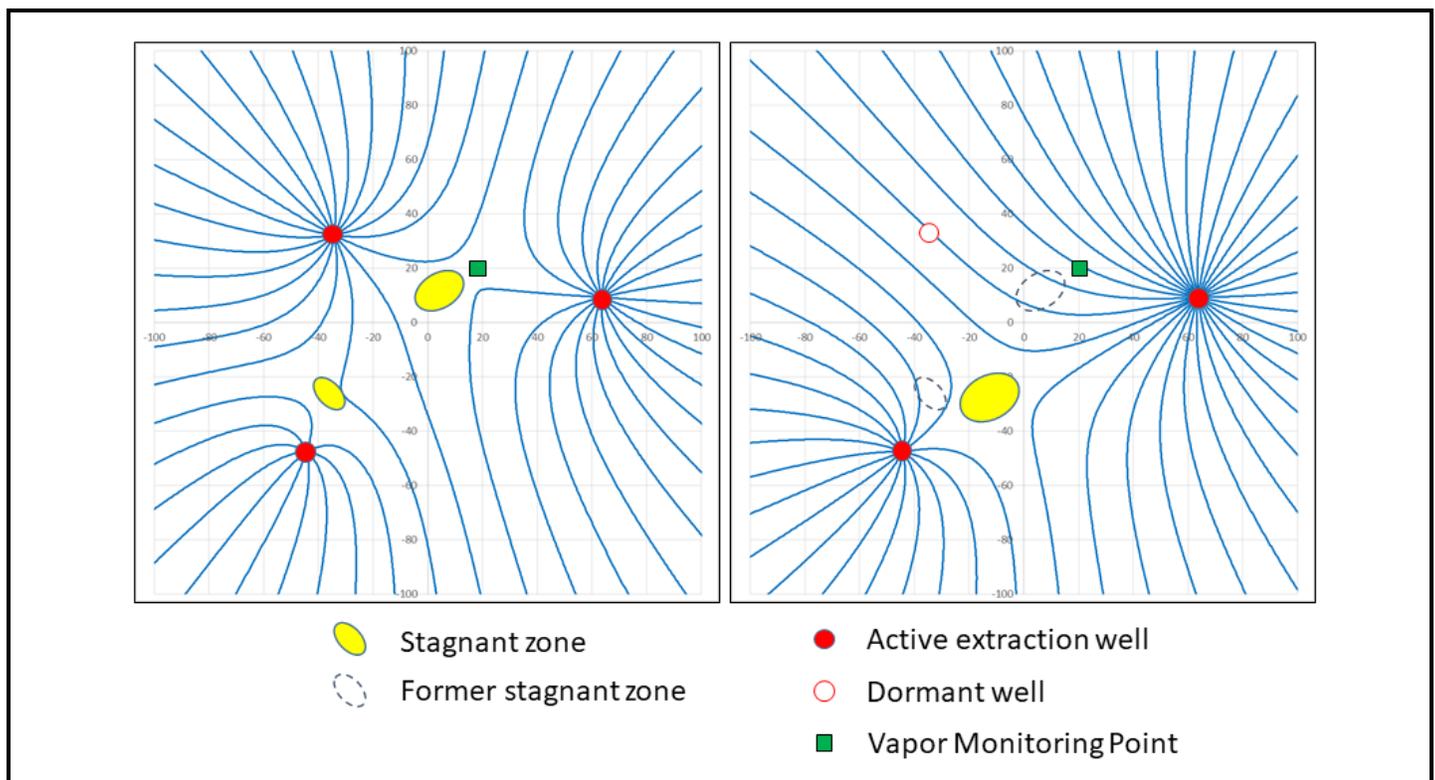
**Figure 8** is oriented to show a site plan. If the source zone is predominantly in the middle of the three wells, very inefficient flushing occurs as most of the flow and flushing occurs outside the triangle of wells as illustrated by the low flow near the vapor monitoring point. Hence, more efficient approaches, assuming a single well has insufficient radius of effectiveness, is to rotate operation among two of the wells at a time to mitigate the stagnation zone impact as illustrated on the right-hand side of **Figure 8** and the much higher flushing rate through the probe location. Another approach would be to rotate among the wells operating one at a time to eliminate all stagnation zones during operation.

To illustrate the impact of stagnation zones, the vapor concentration history at the vapor monitoring point shown in **Figure 8** is provided in **Figure 9**. The vapor point has a nest of three probes (5, 25, and 35 ft below the surface) and the extraction wells are screened from 35 to 50 ft below the surface. The initial operation utilized the two-well configuration shown on the right-hand side of **Figure 8** and flushing reduced the vapor concentration rapidly (“Outside Stagnation”) at all three depths as illustrated in **Figure 9**. However, the third well was added and flow occurred at an elevation of 35 ft below surface as illustrated on the left side of **Figure 8**. The deep probe increased in concentration (“Inside Stagnation”) to near initial levels. The shallower probes were flushed in both configurations primarily by vertical flow downward from the surface to the deeper extraction wells. Without these concentration histories, if all three wells were operated without rotation, the probe at 35 ft would falsely suggest a persistent source area.

A second approach to mitigating stagnation zones is to utilize vent wells. However, passive injection is

unlikely to provide sufficient flow at most sites. If rotation of extraction wells is insufficient for flushing persistent source zones, active air injection can be considered. However, the system should be designed so that any air injected into the system does not pressurize the subsurface and cause VOCs to escape to the atmosphere. The flow rate of injected air is expected to be relatively low compared to the gas extraction rate in the closest extraction wells. The most common use of air injection is to introduce oxygen into the vadose zone when aerobic degradation is oxygen limited.

The previous discussion involves horizontal stagnation zones but an often-overlooked source of stagnation zones are vertical barriers such as surface covers and the water table. If contamination exists under a concrete slab, deeper SVE can create a significant vacuum beneath the slab, but flow will not occur and the VOC vapors will persist. This condition can be alleviated with the installation of vents just beneath the slab. Similar conditions exist at the capillary fringe; no upward flow occurs for flushing unless air sparging is applied in the groundwater.



**Figure 8.** Conceptual streamlines and stagnation zones during SVE

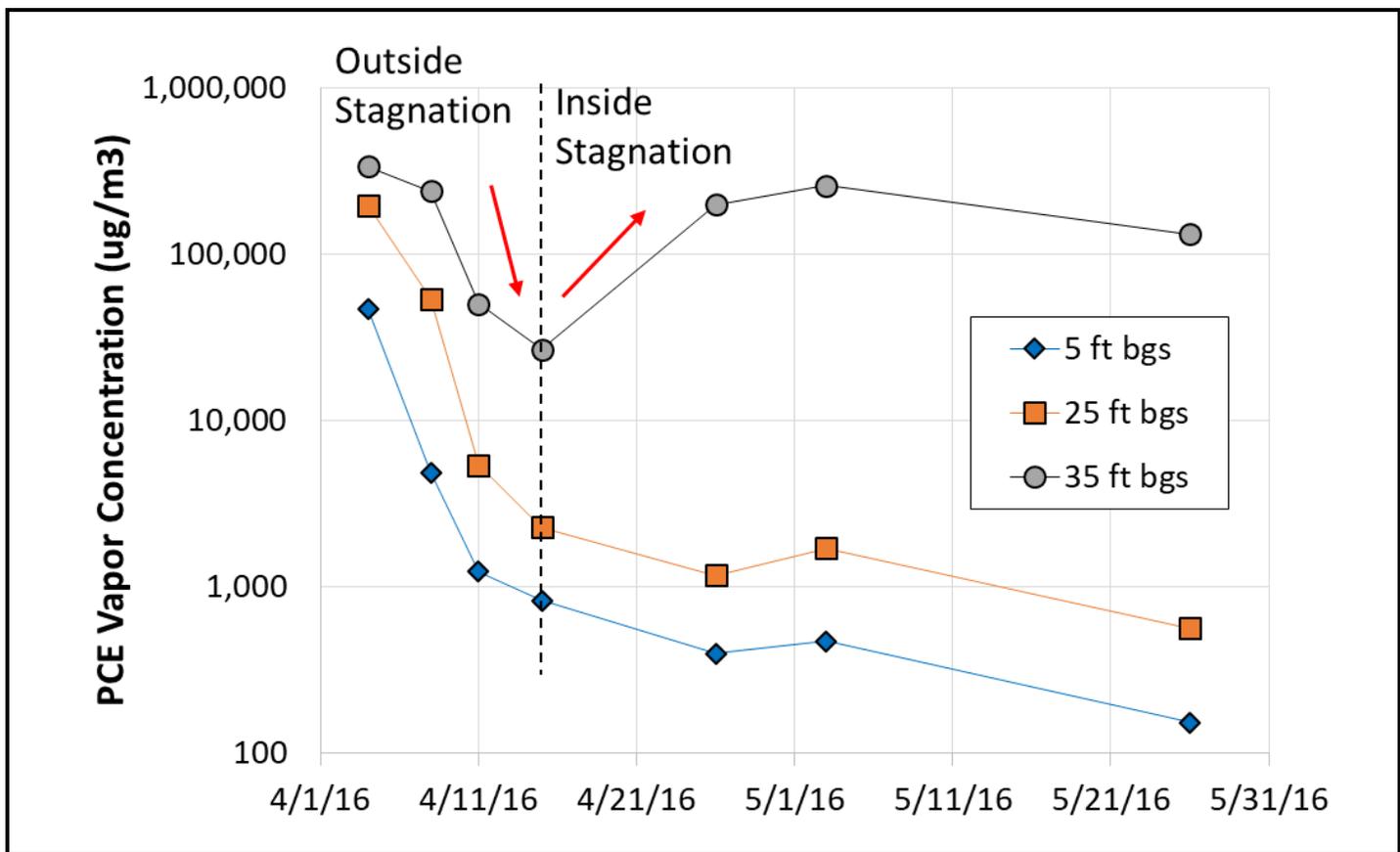


Figure 9. Vapor concentration histories during SVE well rotation

System optimization also involves re-evaluating system components such as the vapor treatment system. The most common consideration at hydrocarbon sites is transitioning from a thermal to a catalytic oxidizer to save on supplemental fuel and then from an oxidizer to GAC to treat low VOC concentrations in off-gas. These transitions are discussed in detail in U.S. ACE (2002) and U.S. EPA (2006).

A second area of system optimization is the use of new extraction or monitoring wells. These can be installed after drilling into suspected persistent source areas during a supplemental characterization effort or after confirmation borings reveal a previously unknown source. New extraction wells may also be justified if existing extraction wells have very long screen intervals that draw primarily dilution air from shallow soils while diminishing flow through deeper, contaminated soils. The pressure drop associated with gas flow through the well screen and upward to the surface is routinely neglected; however, for typical

extraction rates the pressure drop along the screen as flow enters the well can limit the utility of installing longer screens. Vertical profiling of gas flow in extraction wells with PneuLog rarely measures uniform flow along the well screen (Lloyd “Bo” Stewart, pers. comm. 2018)).

For sites that are capped, insufficient flow may occur in the shallow contaminated soil above the top of the screen interval as identified by monitoring points or vertical profiling. In this case, the cap could be removed or perforated, or passive vent wells can be installed. Extraction wells that are no longer in service are also good candidates to act as passive or active vent wells to mitigate stagnation in source areas.

#### 5.4 System Transitions and Vapor Intrusion Mitigation

When evaluating SVE performance for completion or a transition to another technology or objective, multiple lines of evidence are considered. A first step is to perform rebound testing. Rebound testing can

identify persistent source zones to focus future extraction configurations, assess progress toward completion, and refine the conceptual site model. The two-domain SVE model equations presented previously are applicable with the gas extraction rate set to zero for a defined period. When the extraction is restarted, observed increases in extracted VOC concentration and mass removal rate are indicative of the remaining sources (U.S. ACE, 2002) as are the rate and magnitude of rebound in contaminant concentrations at monitoring points. The interpretation and utility of periodic rebound testing is also described in detail in Brusseau et al. (2010, 2015).

An example SVE rebound data set is illustrated in **Figure 5**. The pilot test data plotted in **Figure 3** suggested a small persistent mass of TCE existed in a low permeability soil horizon near a building. The mass was deemed to be small but sufficient to pose a vapor intrusion risk. After the initial 3-day pilot test, a 17-day pause (first rebound period) was followed by extended extraction over 60 days and then a second rebound period as shown in **Figure 5**. The second rebound period was evaluated with a 6-hour extraction period to mimic extraction and sampling performed at the start of both the pilot test and the extended extraction period. The model described in the previous section was fit to the concentration data and provided an excellent fit throughout both the extraction and subsequent rebound periods. The results show the extraction achieved a reduction in TCE mass and concentration of more than 90% within the source zone. The results from that site also illustrate the efficacy of using an SVE well proximate to a contaminant vapor source in the vadose zone for vapor intrusion mitigation. The blower could be operated periodically, as indicated by monitoring data, for short periods to sweep the zone or a smaller blower could be operated continuously to prevent vapors from approaching the building subslab.

Conceptually, vapor intrusion mitigation—where a negative pressure is maintained below a subslab—is a special case of SVE. However, the performance

objective differs. Preventing vadose zone vapors from entering a building is not the same as extracting contaminant mass to attain cleanup, although mass removal during SVE may achieve the mitigation objective. The use of SVE within the deeper vadose zone for vapor intrusion mitigation emphasizes capturing vapors prior to approaching the subslab rather than the maintenance of subslab depressurization. If contaminant vapors emanate from sources deeper in the vadose zone, maintenance of subslab depressurization can result in contaminants being drawn toward the subslab for capture.

In evaluating SVE performance, operators may conclude that SVE alone is inadequate to achieve vadose zone cleanup objectives in an acceptable timeframe. However, the location and rate of contaminant mass removal may successfully meet mitigation objectives with no modification to nearby buildings. The efficacy of this type of application or even the initial use of SVE solely for vapor intrusion mitigation is evolving (Lutes et al., 2017; Schumacher et al., 2017, Truesdale et al., 2016).

The design of an SVE system solely for vapor intrusion mitigation or the transition of an existing system to meet these alternative objectives follows the identical design concepts as those described in Section 4,

- Installation and operation of a pilot extraction screen proximate to sources of contaminant vapors to determine site properties and the radius of effective contaminant vapor reduction (subslab vacuum responses may be negligible even though concentration reduction is achieved)
- Evaluation of vapor concentration rebound to assess the frequency of sweeping the vadose zone pore volume to maintain a relatively low vapor concentration (compared to the source concentration)
- Assessment of the surface area to be protected and the total gas extraction rate requirement to achieve the frequency of pore volume sweeps

- Placement of extraction screens within or near the vapor sources
- Selection of vapor treatment and system installation (based on a cost analysis, the preferred approach may be a fixed system or periodic use of a mobile system)
- Operation of the system with particular attention to minimizing the impact of stagnation zones (substantial subslab vacuums may be created with no effective flow through the zone; vent wells may be beneficial).

If transitioning an existing system, the infrastructure is likely in place and the design will consist of determining the optimal extraction strategy.

The design and performance evaluation criteria in this EIP were applied to a site with contaminated groundwater acting as the sole source of vapors migrating upward through the vadose zone as described in Section 9.2 and Appendix B. The evaluation provides a robust basis to determine the most cost-effective, site-specific implementation of vapor extraction in a former groundwater monitoring well to meet vapor intrusion mitigation objectives for a downgradient dissolved plume under buildings.

## 6 SYSTEM SHUTDOWN AND SITE CLOSURE

As an SVE system begins to show evidence of the diminishing contaminant removal rate illustrated in previous sections, SVE performance needs to be evaluated against the site-specific performance objectives. In particular, this evaluation may determine whether the system can be terminated, optimized, enhanced, or transitioned to another technology to replace or augment SVE.

Recent guidance from the U.S. DOE (2013) specifically addresses the elements of this type of performance assessment. The guidance summarized and built on previous guidance for SVE design, operation, optimization, and closure from the U.S. EPA (2001), U.S. ACE (2002), and AFCEE (2001).

The framework and steps for making SVE remedial decisions described in the guidance are applicable to all SVE sites. The framework is summarized in this section. A spreadsheet model (SVEET) associated with the U.S. DOE guidance is available to the public and treats both source scenarios illustrated in **Figure 6** as a single monolithic layer in the vadose zone that does not decay.

Periodic SVE shutdowns to evaluate rebound will provide information necessary to assess progress toward remedial goals of absolute vapor concentrations or mass fluxes. An initial rebound test performed after the initial decay in extracted concentration will provide an indicator of source zones and a baseline for later comparison. The periodic evaluations illustrated in **Figure 5** demonstrate a reduction in average source concentration of more than one order of magnitude.

Over time, the cases of local rebound concentrations above applicable cleanup criteria are expected to decrease. Rebound testing will help identify locations where persistent high VOC levels warrant additional investigation for potential augmentation or locally aggressive treatment with an alternative technology (e.g., chemical oxidation, electrical resistance heating). Additionally, transport and exposure models can be used with rebound test results to estimate whether system closure may pose a risk to potential receptors.

Methods for evaluating the rebound data are provided in U.S. ACE (2002) as summarized in Section 5.2. Additional details on the interpretation and use of periodic rebound testing are described by Brusseau et al. (2010, 2015). The key results from the rebound testing are reductions in equilibrium VOC vapor concentrations and VOC mass flux rates from the residual VOC sources. The use of these results as inputs for fate and transport modeling after SVE ceases is described at the end of this section.

## 6.1 Framework for Assessing SVE Termination or Technology Transition

The U.S. DOE guidance (2013) presents a logic process for decision makers to determine if (1) the site is ready for SVE termination and closure, (2) the existing SVE system should be optimized to improve performance, or (3) alternative technologies should be considered to meet remediation goals. The primary focus is to identify if and when SVE can be terminated based on assessments of the residual VOC mass remaining in the vadose zone, the expected VOC mass flux towards groundwater and towards the land surface (vapor intrusion), and the longevity of the source under natural attenuation. If the remediation goal is unlikely to be attained through optimization or a reasonable period of continued SVE, then potential alternative approaches and enhancements can be considered as described in Section 8. These alternatives are introduced in the context of enhancing, augmenting, or replacing SVE technology at specific locations at a site.

Before assessing SVE termination or transition, the components and phases of the SVE operation can be reviewed for completeness and appropriateness as follows:

### Site characterization and conceptual site model

- Adequate characterization of the original source mass and location
- Determination of LNAPL or DNAPL presence, age, amount, etc.
- Adequate characterization of the subsurface soils/geology including heterogeneity, preferential flow paths, any vapor confining units, etc.

### SVE system design

- Appropriate well spacing and flows given the characterization
- Appropriate monitoring well and probe distribution (horizontal and vertical)
- Adequate monitoring instrumentation and data collection methods

### Operations and monitoring

- Appropriate and adequate data collection frequency to define trends
- Avoided prolonged stagnation zones and performed rebound tests
- Relatively accurate and comparable calculation of mass removal rates to estimate original VOC mass
- Diminishing mass removal rates, caused by mass depletion and mass transfer constraints and not a result of poor design or uncharacterized sources

### Performance assessment

- Diminishing mass removal rate that is consistent with diffusion rate-limited vapor transport
- Models of vapor diffusion predict commensurate values to the observed mass removal rate during operations using the maximum observed concentrations during rebound and a characteristic length scale for diffusion determined from the site geology
- Relatively accurate forecasts of system performance using models commensurate with those of Section 5.2 with only modest adjustment to fitted parameters over time
- Rebound concentrations that can be correlated to VOC concentrations in fine-grained units or underlying contaminated groundwater

Based on the analysis of the SVE phases described above, the determination of appropriate site goals described in Section 2.3, and likely impacts from remaining VOC sources, the following three-step decision logic summarizes the determination of appropriate future actions at a site detailed in **Figures 10a and 10b** (see U.S. DOE, 2013 for the chart):

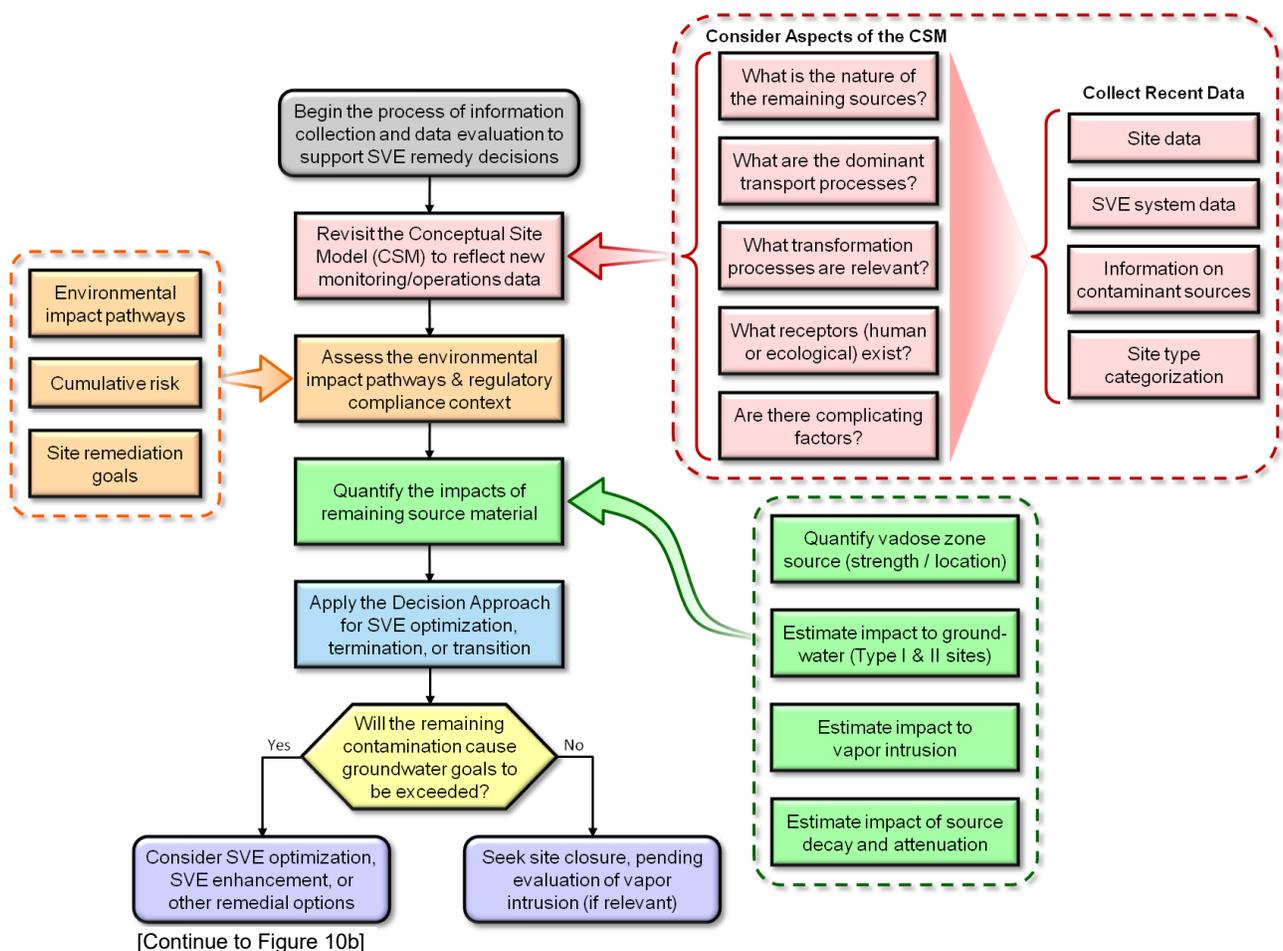
1. If SVE is shut down, will remediation goals be met, based on cleanup levels and lines of evidence? Could residual contamination cause groundwater or indoor air goals to be exceeded? Could residual contamination necessitate the installation and operation of a

vapor intrusion mitigation system for indoor air exposures? If the answer to these questions is no, proceed to Step 2.

2. Has the existing SVE system been optimized to remove subsurface contaminant mass more effectively and allow for ideal closure conditions? Is significant VOC mass remaining in permeable zones? Is SVE reducing VOC contaminant source strength? Will the current VOC removal rate allow for remediation goals to be met within a reasonable timeframe? If reasonable optimization options for SVE have been exhausted, proceed to Step 3.
3. If optimization of the current SVE system is complete and performance objectives for active SVE have been met, SVE termination

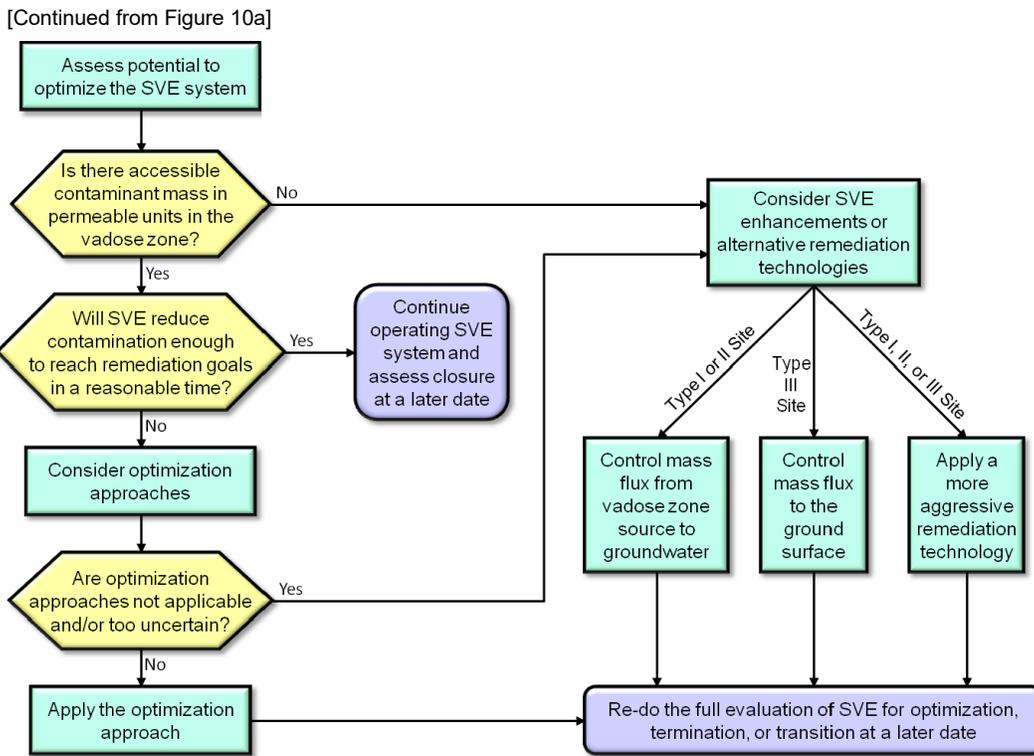
and possibly site closure can proceed if quantification of remaining sources and impacts are acceptable. U.S. DOE guidance (2013) provides background and a recommended approach for this quantification building on previous work. Methods for quantifying residual sources and impacts on groundwater and vapor intrusion are described in Section 6.2.

If the assessments in Section 6.2 of remaining sources indicate attaining performance objectives is not feasible with conventional SVE alone, SVE enhancement or augmentation may be possible as described in Section 8.



Source: U.S. DOE, 2013

Figure 10a. Decision flowchart for SVE system optimization, transition, and closure



Source: U.S. DOE, 2013

Figure 10b. Decision flowchart for SVE system optimization, transition, and closure

## 6.2 Summary of Methods for Evaluating Attainment of SVE Endpoints

SVE termination and site closure criteria must consider general VOC mass transfer limitations and site-specific performance limitations of SVE in the context of remedial action objectives (RAOs) based on potential human health or environmental risks (Switzer, 2004; U.S. ACE, 2002, U.S. DOE, 2013). The most common method for determining SVE site closure criteria is the assessment of potential aquifer degradation from the transport of contaminants from the vadose zone to the groundwater. A typical requirement is the attainment of specified soil concentrations or vapor concentrations based on the premise that mass flux from the vadose zone to groundwater not result in levels exceeding MCLs (or other regulatory limits or RAOs).

The simplest interpretation of this requirement is the attainment of equilibrated rebound concentrations that do not exceed MCL-equivalent vapor

concentrations (i.e., vadose zone porewater at or below MCL). For example, TCE at about 5 ppb in water equilibrates to about 350 ppb in soil vapor, providing a target value independent of SVE trends. However, this approach could result in soil

remediation efforts beyond what is necessary for protection of groundwater or other remediation goals. For these reasons, the evaluation of aquifer degradation could also include consideration of mass fluxes after SVE ceases and attenuation processes that reduce the concentration of VOCs in groundwater and the vadose zone over time and with distance from the source.

These more complex evaluations involve modeling the fate and transport of residual contaminants in the vadose zone into underlying groundwater with a cleanup goal in the vadose zone back-calculated to a residual source concentration in the vadose zone that does not result in a groundwater exceedance of MCL at a specified aquifer location. One of the first such

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modeling assessments resulted in the U.S. EPA production of the widely used, but overly simplistic, VLEACH model (Rosenbloom et al., 1993).<sup>2</sup> Of note, SVE operations continue as of the date of this publication at the first example site for VLEACH from 1993. Updated models for assessing the impact to groundwater are described in Section 6.3.

Vapor intrusion into buildings, especially ground-level and sub-ground floors, is of particular importance for VOCs in the subsurface. The current version of EPA's *Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air* (U.S. EPA, 2015) provides current technical and policy recommendations on determining if the vapor intrusion pathway poses an unacceptable risk to human health at cleanup sites. This guide presents a framework for assessing the potential for harmful concentrations of VOCs in buildings.

The EPA guide leads the decision maker through an evaluation process based on multiple lines of evidence of the potential for harmful vapor intrusion. If the soil gas VOC concentrations exceed indoor air vapor intrusion screening levels, additional sampling may be warranted. If VOC concentration in the indoor air is above action levels, and the source is likely subsurface, then vapor intrusion mitigation may be warranted. Because the vapor intrusion exposure pathway can be strongly influenced by the specific structures and conditions in the subsurface, at the ground surface, and within buildings, it can be difficult to model and assess accurately. Existing vapor intrusion analyses, therefore, often rely on surface-based measurements and analyses as lines of evidence. However, this is an area of active research and recent tools have been published by U.S. DOE (2016) for the assessment of site-specific vapor intrusion based on vapor-phase diffusion from residual vadose zone source mass.

### **6.3 Models for Evaluating Impacts of Residual Mass in the Vadose Zone**

Termination of SVE requires an assessment of impacts from residual mass in the vadose zone as described in Section 6.2. Such assessments are based on the quantification of the VOC mass flux into underlying groundwater or into buildings on the surface. The flux into groundwater yields a calculated VOC concentration in groundwater using a mixing approach that varies among models and generally ignores existing groundwater contamination. The calculated groundwater concentration is the primary method to assess groundwater impact.

Mathematical calculation of vapor intrusion impacts is less developed; however, the same concepts of mass flux across a vertical barrier (e.g., concrete slab) followed by mixing inside a surface enclosure (e.g., basement) undergoing an exchange with the surrounding atmosphere suggest the modeling can be very similar. In general, lateral transport is conservatively neglected, leaving vertical transport from residual sources in the vadose with upper (surface) and lower (water table) boundary conditions as the basis for mathematical modeling of vapor concentrations and fluxes.

As mentioned above, an early mathematical model available from U.S. EPA is VLEACH (Varadhan and Johnson, 1997) and it is widely utilized. However, the underlying assumptions are overly simplistic and result in predictions that are inconsistent with observations during SVE and in post-SVE monitoring. The VLEACH model assumes the vadose zone soil is homogeneous despite the observed mass transfer constraints observed in essentially all SVE applications. Typically, soil property measurements are averaged for VLEACH and result in higher diffusion rates from source soils than reality. Measured vapor concentration profiles are calculated to dissipate quickly, on occasion faster than observed during active SVE, and the model

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<sup>2</sup> Available for download from <https://www.epa.gov/water-research/vadose-zone-leaching-vleach>.

over-predicts the flux entering groundwater. In addition, two boundary conditions are available at the water table. A zero vapor concentration (i.e., immediate dissolution into groundwater) can be specified that over-predicts the entering flux. Secondly, a zero concentration gradient can be specified such that mass only enters groundwater via infiltration of contaminated porewater; however, the infiltration rate is very difficult to predict. Sites in arid climates may experience extensive evapotranspiration yielding a negative infiltration rate. Finally, VLEACH is needlessly numerical and can be solved analytically as derived by DiGiulio et al. (1998). DiGiulio et al. (1999) and DiGiulio and Varahan (2001b) also extended the choice of boundary conditions and methods of assessment.

SESOIL (Hetric and Scott, 1994) is also an early model occasionally used to calculate the fate and transport of VOCs in the vadose zone; however, the model is not applicable to this scenario. In the SESOIL model, downward movement of pollutant occurs only with the soil moisture, while upward movement can occur only by vapor phase diffusion. For sites applicable to SVE, downward vapor diffusion generally contributes much more significantly to contaminant transport than downward soil moisture migration and cannot be neglected.

The difficulties in modeling the interaction of the vadose zone and groundwater are well described by Truex et al. (2009):

*The use of analysis techniques needs to be considered in the context of the dominant mode of contaminant transport within the vadose zone ... As vapor-phase transport becomes more important (e.g., for arid sites with low aqueous recharge), three-dimensional contaminant movement in the vadose zone may be more important, the contact area of vadose zone contamination on the water table is more difficult to estimate, and transport of contaminants across the water table includes a mass transfer resistance. Thus, when vapor-phase transport is significant, these issues should be considered in terms of computing contaminant flux to the ground water and the resultant ground water contaminant concentrations.*

As a result of the limitations in the early models and the complexity of the boundary condition at the water table, researchers continue to develop methods to examine the interaction of vadose zone contaminants with the groundwater in the context of SVE performance (Carroll et al., 2012; Oostrom et al., 2010; Truex et al., 2009). These approaches and those in U.S. ACE (2002) estimate the residual mass as well as the mass transfer coefficient (or utilize a one-dimensional diffusion model) to assess the mass flux from a residual source and then assume various interactions with the underlying groundwater. Numerous specific scenarios can also be calculated using methods and spreadsheets provided in U.S. DOE (2013). This approach can also be integrated into the framework of VLEACH, where a numerical formulation exists, by allowing soil properties and water saturation to vary with depth and by implementing more realistic boundary conditions at the water table. These variable properties can be correlated to the site-average mass transfer coefficient between the advective and diffusive soils (U.S. ACE, 2002) as described in Section 5.2. The SVE estimated fractions of advective versus diffusive soils can also be utilized to validate more realistic models of source soils. In addition, more complex water table interactions are necessary to provide realistic estimates of the vadose zone mass flux entering groundwater, or potentially, the mass flux of contaminant entering the vadose zone from contaminated groundwater. Recall from Section 5.2, SVE data can also be used to estimate a mass transfer coefficient for the interface between the vadose zone and groundwater, if groundwater is contaminated at the start of SVE.

Example results utilizing VLEACH modified to include a layered vadose zone with varying physical properties and water saturation and a more realistic interaction with contaminated groundwater are provided in **Figure 11**. The plots on top illustrate vapor concentration profiles calculated after SVE ends. The plots on the bottom provide a mass balance over time for calculated mass remaining in

the vadose zone, cumulative mass entering groundwater, and cumulative mass lost to the atmosphere through the soil surface. The layered soil model results on the left were calculated by varying soil properties in VLEACH with depth, particularly a tighter soil interval in the deep vadose zone with a high moisture content. The uniform vadose zone soil model results on the right were calculated with VLEACH as downloaded from the EPA Web site and averaging the measured soil properties.

The layered model profiles are observed to maintain nearly the same shape for all the times providing a limited validation of using a layered model, whereas the uniform soil model rapidly approaches an

unrealistic uniformity that is not consistent with initial profiles or the results observed during SVE at the site. The layered model was further validated by comparing calculated mass flux rates from tight layers with those calculated using the mass transfer coefficient estimated from SVE operations, as described in Section 5.2, and a concentration gradient between permeable and tight soils. The mass balances between the two models were significantly different as the uniform soil model suggested most of the residual mass in the vadose zone at the end of SVE would enter groundwater within a couple of decades, with smaller losses to the atmosphere, and a relatively clean vadose zone within about 50 years.

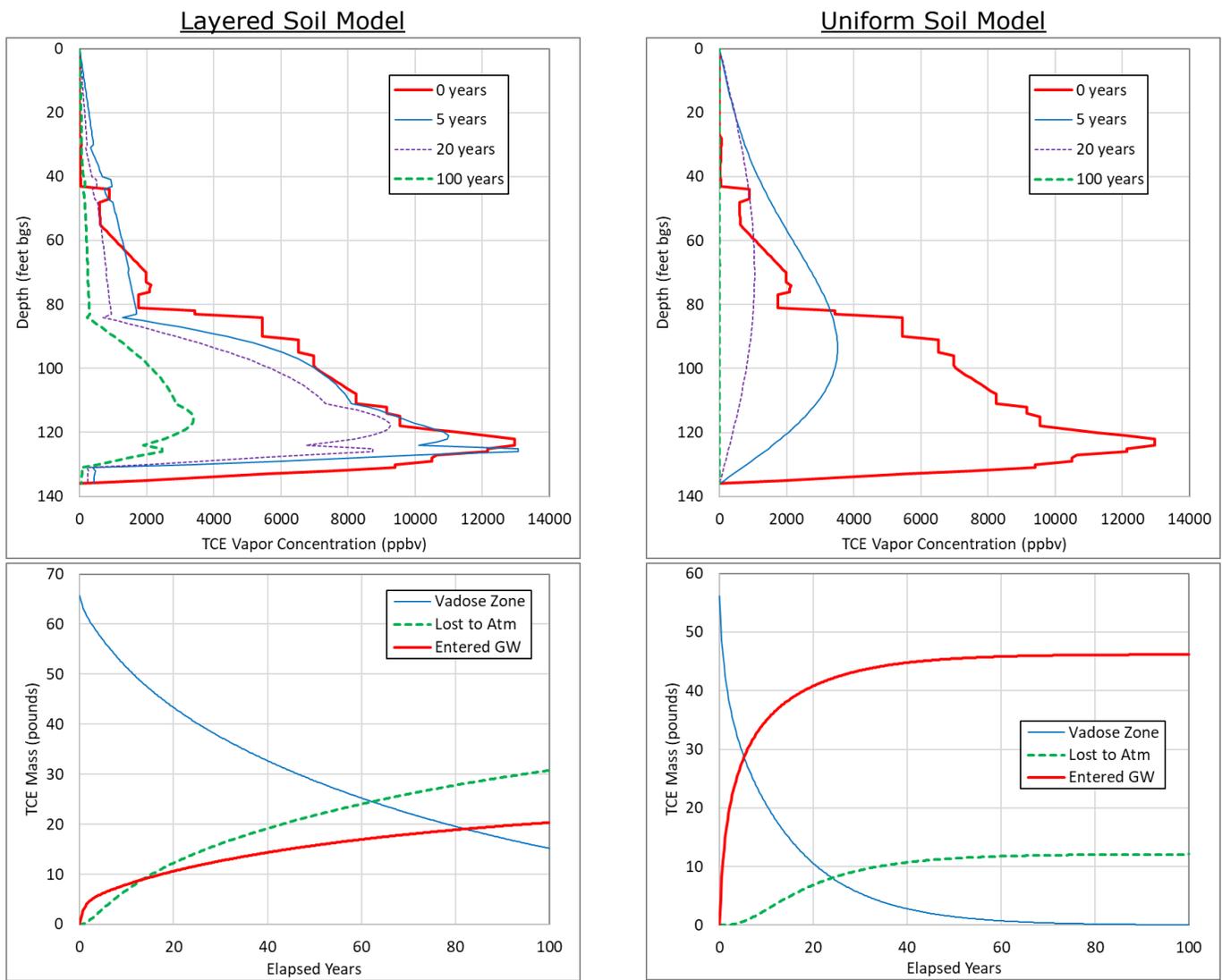


Figure 11. Comparison of modeled vapor concentration profiles and mass balances for layered and uniform soil models

Conversely, the layered model, correlated to SVE operational results, indicates the mass will remain in the vadose zone for much longer with significantly slower entrance to groundwater and a higher proportion of the mass lost to the atmosphere at the surface. A mixing model was used to calculate groundwater concentrations resulting from the calculated mass flux at the water table and the results compared very well with historical groundwater concentrations observed in a nearby, downgradient monitoring well, including a trend of decreasing groundwater concentration observed during several years of SVE.

## **7 COST CONSIDERATIONS FOR SVE SYSTEMS**

As described in Section 2, SVE, either alone or in conjunction with other treatment technologies, has been selected as the remedial action at more than 285 Superfund sites (U.S. EPA, 2012a), and has likely been used for thousands of non-Superfund cleanups, such as SVE treatment of leaking underground petroleum storage tank sites. Cases of successful implementation of SVE treatment technology have been documented at both the federal and state level, and more than two decades ago EPA designated SVE as a presumptive remedy for VOCs in soils at Superfund sites (U.S. EPA, 1993). At the state level, a study conducted by the California State Department of Toxic Substances Control indicated that SVE was the most frequently selected cleanup alternative for carcinogenic VOCs in vadose zone soils (CalEPA, 2010).

Thus, there is much information and experience available from federal, state, and local authorities on actual SVE system costs and long-term performance. However, SVE system design, installation, operation, and maintenance costs vary significantly based on site conditions. Some of the more important considerations are listed below, but the reader is also referred to the cited references in this section for more detailed information on costing an SVE system,

and to a qualified remediation engineer for designing and costing an actual SVE system for a specific site.

### **7.1 System Design**

SVE systems may be designed from the ground up or a packaged system may be available for rent or purchase from various vendors. SVE systems designed from the ground up may be more expensive to design and construct than an off-the-shelf packaged system. While using a packaged system may reduce design and construction costs (Goldstein and Ritterling, 2001; U.S. EPA, 1997b), it could increase the operational cost if the extraction blower or treatment train are not appropriately sized for site-specific conditions.

### **7.2 Cost Components**

SVE system capital costs typically include extraction and monitoring well construction; vacuum blowers (e.g., regenerative, positive displacement, or centrifugal); vapor and liquid treatment systems piping, valves, and fittings (usually plastic); and instrumentation to support system operation, monitoring, and maintenance (U.S. EPA, 1997b). Most of these SVE system components are readily available off the shelf. However, the exact system design, configuration, process components, layout, operation, and maintenance of the extraction and monitoring system is strongly influenced by site-specific factors including the properties and concentration of contaminants; the areal and vertical extent of contamination; system size (number of extraction wells and blower size); the need for and complexity of off-gas treatment; and the length of time the system must be operated to reach cleanup targets (U.S. EPA, 2001). System design modifications may also be required after installation depending on the actual operating conditions and system performance.

### **7.3 Operation and Maintenance**

Operations and maintenance costs for SVE systems include labor, electrical power, maintenance, monitoring, and air and groundwater treatment

activities. SVE system components are highly reliable and are capable of continuous operation for the duration of the cleanup without constant operator oversight. Controls are often integrated to allow for the automatic shutdown of the system if conditions indicate component failure. If the system shuts down, the controls can be designed to immediately notify the operator so that component failure can be identified and repairs made quickly for minimal downtime. In terms of off-gas and groundwater effluent, cleanup costs can significantly increase if both require treatment (FRTR, 2008). Air emissions treatment and testing is often the most costly component of an SVE system (AFCEE, 2001). Electric power costs can vary significantly by location (i.e., local utility rates and site conditions).

#### **7.4 Cost Estimating Tools**

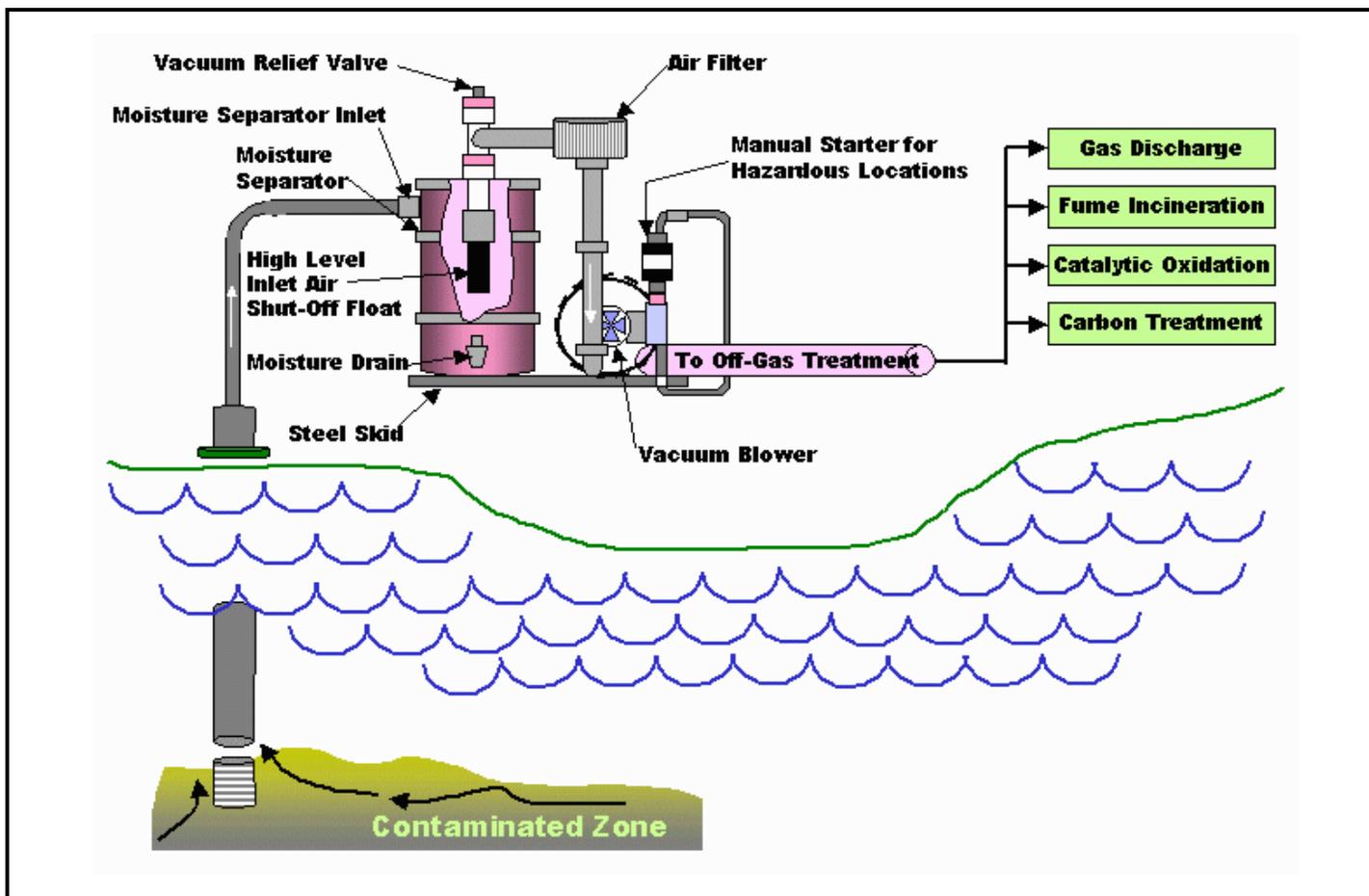
Because most SVE system components are available off the shelf, RSMeans (2017) or other standard construction cost estimating tools may be used as a resource for costing various SVE system components such as parts and labor for installation of subsurface piping, electrical equipment, and treatment system components. For costs specific to SVE systems (as well as ancillary remediation technologies such as bioventing and air sparging), use FRTR's Remedial Action Cost Engineering and Requirements (RACER) software (FRTR, 2016). RACER is a PC-based system originally developed in 1992 by the U.S. Air Force that uses a methodology for generating location-specific cost estimates for remediation technologies. RACER allows the user to select the desired models from a list of available technologies (including SVE), define the required parameters in the selected technology, and tailor the estimate by verifying and editing secondary parameters. RACER uses current multiagency pricing data, and is researched and updated annually to ensure accuracy. In addition to users within the federal government, RACER is used by a variety of state regulatory agencies, engineering consultants, facility owners and operators, financial institutions, and law firms.

FRTR (2008) includes various RACER outputs, links to ancillary technologies, references, and typical system design diagrams for SVE systems (**Figure 12**). FRTR (2008) also provides an example detailed cost analysis developed in 2006 using RACER for “easy” and “difficult” SVE remedial actions at “small” and “large” sites, with total costs ranging from \$80,295 for an “easy” and “small” site, to \$368,465 for a “difficult” and “large” site. Note that it is not clear what level of off-gas or collected groundwater treatment is included in the operating and maintenance (O&M) line item, which may be a significant cost at some sites.

Caution is recommended in using these costs and references in the context of an actual site cleanup because the base year of the estimates varies and because the contaminant properties, site characteristics, and performance objectives may differ significantly from the conditions at the specific site of interest. In short, SVE costs are highly variable due to site-specific variation in critical parameters that can impact the SVE process and how these characteristics can change over time, and this variability must be considered to get adequate cost estimates for site-specific applications of SVE.

## **8 SVE ENHANCEMENTS AND COMPLEMENTARY AND PASSIVE TECHNOLOGIES**

When evaluating the termination of active SVE, a number of SVE system enhancements can be undertaken to hasten cleanup by focusing on the more persistent VOC sources revealed during SVE operation (U.S. EPA, 1997a). If SVE enhancements are unlikely to complete the cleanup in the timescale desired, transitioning to another complementary technology may be needed. Alternatively, at sites where cleanup timescales are less critical or cleanup activities are nearing an end, passive SVE systems can be a cost-effective and low-impact alternative to maintaining active systems. Finally, a flux control approach can be implemented by sequestering the remaining VOC mass rather than extracting or



Source: FRTR, 2008

**Figure 12.** Typical in situ soil vapor extraction system

destroying the mass in place. However, flux control is the least desirable of these alternative approaches as it does not reduce the source of VOCs.

### 8.1 Potential Enhancements to an Existing SVE System

If SVE alone is not successful in meeting remediation objectives, other cleanup technologies can enhance SVE to hasten attainment of cleanup goals. In these cases, SVE is still part of the technology, but other mass removal mechanisms are added or enhanced to address zones of persistent source concentrations. These technologies can be applied to small mass fluxes after SVE has largely removed the source, or where SVE alone is unlikely to attain further significant source reduction. Preference is given to

technologies that make use of the existing SVE infrastructure (wells, piping, blowers, etc.) and leverage the capital investment for SVE.

**Bioventing.** At sites where the primary contaminants are aerobically biodegradable (or cometabolically degradable<sup>3</sup>), replacing active extraction with air injection provides oxygen to the native bacteria and stimulates additional contaminant removal without the cost of off-gas treatment. This approach is widely applied at petroleum hydrocarbon sites. Air injection can be pulsed, with the pulse frequency and duration based on observed oxygen uptake rates. Existing wells, piping, and blowers can often be used. The addition of gaseous nutrients (e.g., nitrous oxide, triethyl phosphate) can be used to maximize

<sup>3</sup> Cometabolism is the simultaneous degradation of two compounds, in which the degradation of the second compound depends on the presence of the first compound.

degradation rates, although many sites have been addressed without nutrient addition (Leeson and Hinchee, 1996; U.S. EPA, 1995).

**Multiphase Extraction.** Multiphase extraction simultaneously extracts vapors and liquids from the same well, using either a single vacuum pump or separate pumps for the separate phases. The liquid extraction may enhance the removal of mass from the location of the smear zone/capillary fringe by lowering both the water table and levels of soil saturation. The application of vacuum can also enhance the removal of liquids from soils with modest permeabilities for simultaneous recovery of dissolved mass or LNAPL (bioslurping) from the source areas (U.S. ACE, 1999).

**In Situ Thermal Treatment.** The application of heat to contaminated soil increases the vapor pressures of most organic contaminants and is accompanied by changes in the solubility, viscosity, surface tension, and density of NAPLs. Thermal enhancements are relatively expensive and costs depend on the size of the subsurface zone being treated. Therefore, it is prudent to apply thermal technologies only after SVE reveals zones of persistent contaminants.

Bioremediation rates and hydrolysis (for chlorinated ethanes) may be significantly enhanced at modestly elevated temperatures due to faster reaction kinetics at higher temperatures or the enhancement of biodegradation by robust thermophilic bacteria.

Soil heating is more tolerant of soil heterogeneity than most other in situ technologies. Heat can be introduced through electrical resistivity heating (passing currents between electrodes placed into the soils to be treated), thermal conduction heating (where heat propagates through conduction from heaters placed in wells), or steam injection. The vapors generated by the process are typically collected via vapor extraction wells (Kingston et al., 2010; U.S. ACE, 2014). Recent work has extended the applicability of SVE to emerging contaminants, such as 1,4-dioxane, that are resistant to volatilization because of high water solubility and to biological

degradation with the use of heated air injection to reduce porewater saturation (Rob Hinchee, pers. comm. 2016).

**In Situ Air Sparging.** Air sparging involves the injection of air into wells with short screen intervals below the water table. The injected air moves outwards and upwards from the well based on buoyancy and air-entry pressures of the soil strata, which are closely related to typical pore size and connectedness. If the remaining sources are concentrated near the water table and capillary fringe, the mass may not be easily accessible to SVE. In situ air sparging may allow vertical air passage through these zones for either subsequent capture of the contaminant vapors with the existing SVE system or discharge to the vadose zone and ultimately to the atmosphere. The air also agitates moisture in the capillary fringe and may provide a source of dissolved oxygen to promote aerobic degradation of some compounds in both the groundwater and vadose zone (U.S. ACE, 2013).

**Hydraulic/Pneumatic Fracturing.** Hydraulic and pneumatic fracturing are two technologies that induce fractures in the subsurface to enhance the remediation of contaminants by increasing the effective (interconnected) porosity of subsurface materials. These technologies are particularly useful and cost-effective at contaminated sites with low-permeability soil and geologic media, such as clays, shales, and tight sandstones, where remediation is difficult without some sort of permeability enhancement. However, the usefulness of fracturing technology is not limited to low-permeability sites. Beneficial effects can also be achieved by creating new or enlarging existing fractures in the subsurface, which improves air flow to encourage degradation and removal of contaminants (Riha et al., 2008; Suthersan, 1999b).

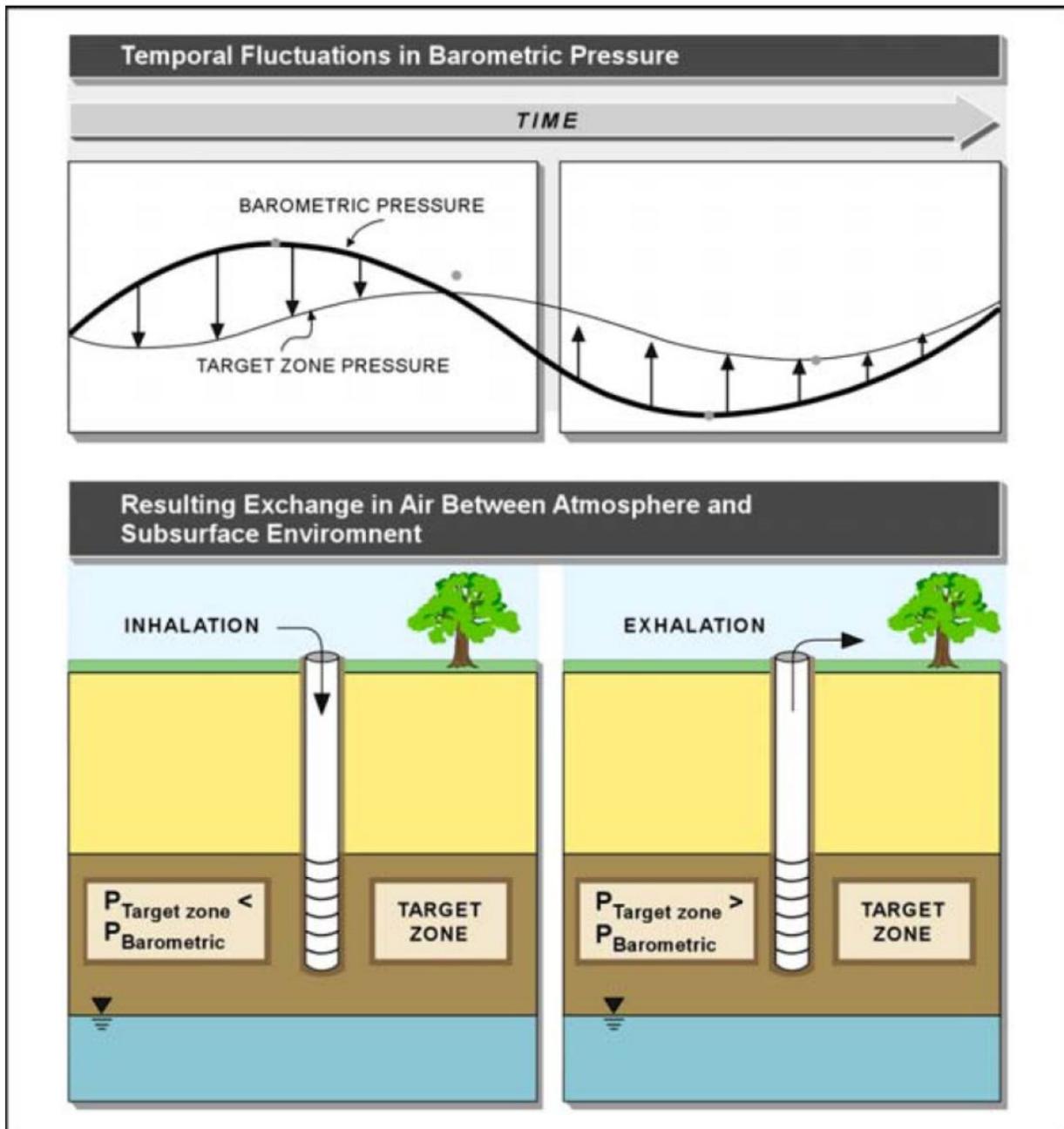
## 8.2 Passive SVE

Typical SVE operations rely on “active” SVE technology, where active vacuum or blower pressure is applied to the subsurface with standard SVE

equipment to induce advective air flow into vapor extraction wells. Passive SVE capitalizes on the use of natural pressure gradients between the subsurface and atmosphere to effect an advective flush in the subsurface (Kuang et al., 2013; SRNL, 2010; U.S. ACE, 2002). A one-way passive mechanical valve is located at the wellhead that allows air to exit the subsurface during diurnal or weather-related pressure outflow periods without allowing ambient air to enter the well otherwise. Passive SVE is often beneficial as

a polishing strategy prior to monitored natural attenuation or formal site closure because of its relative effectiveness in removing low levels of residual contamination, its low operation and monitoring cost, and minimal site disruption.

**Figure 13** illustrates how temporal fluctuations in barometric pressure (based on natural diurnal change or multiday weather phenomena) results in intermittent removal of soil vapors from the vadose



Reproduced from SRNL, 2010

**Figure 13.** Conceptual model for passive 'inhalation' and 'exhalation'

zone (SRNL, 2010). If these natural variations do not produce sufficient flow, microblowers may also be implemented. These small direct current blowers can be powered by renewable energy such as one or two typical solar panels and provide a small but measurable boost in vacuum levels, while still lowering capital costs. Similar to active SVE, passive SVE works more effectively in coarse, high permeability soils. However, passive SVE can work more effectively than active SVE in removing residual contamination from low permeability soils that are dependent on diffusion rather than advective flow for contaminant removal.

Consider using passive SVE when

- Asymptotic conditions are reached at low concentrations with active SVE
- A large number of active SVE wells can be converted to a passive system
- Lower permeability source soils require treatment
- A site is remote and has long timescales for cleanup
- An active site requires minimal surface disturbance and has long timescales for cleanup.

Passive SVE is likely not applicable under the following conditions

- High soil moisture
- Preferential pathways
- Minimal contaminant zone stratification
- High contaminant concentrations causing aboveground treatment needs
- Short cleanup timeframe
- High extraction rates
- Large number of new wells.

Similarly, bioventing can be implemented passively as described above but with a reversal in the flow direction. NFESC (2000) evaluated the applicability of passive bioventing at 15 U.S. Department of Defense sites.

## 9 CASE STUDIES

Two case studies from actual SVE-remediated sites are provided to illustrate the application of the concepts and methods described in this EIP. Case Study #1 illustrates how one can address a newly emerged, small, but persistent source at an existing SVE site by using limited SVE testing, past data, and modeling to assess past and future mass removal and optimize a system to close a site. Case Study #2 provides an example of how one can assess the potential for groundwater to recontaminate a site after SVE cleanup by using SVE operational data and modeling at a site with potential vapor intrusion exposures. Each case study is summarized below with more detailed site descriptions in Appendices A and B for Case Study #1 and #2, respectively.

### **9.1 Case Study #1: Assessment of a Small Persistent TCE Source**

In the first case study, after years of SVE and attainment of remedial goals in nearly all areas of the site, a small persistent source of TCE emerged during drought conditions as the high moisture content separating the source from permeable pathways dissipated. SVE operations began in 1997 and operated through 2009 extracting over 1,600 lbs of TCE. Several years of monitoring under ambient conditions supported closure until 2014 when the small source emerged and reopened the site for further investigation.

A review of historical boring logs and soil sampling for physical analyses indicated a clayey silt interval existed from a depth of about 25 to 35 ft below ground and likely created some degree of perched water at 25 ft. The lateral extent of such water was not known. The conceptual site model was revised to account for this water and its disappearance during the drought conditions, exposing the interface of the clayey silt to overlying silty sand. In effect, the barrier to volatilization was removed. The contamination in the clayey silt was the result of overflow and leaks of TCE-laden water from oil-water separators. The water migrated downward and seeped into this fine-

grained interval and remained relatively pristine with respect to TCE concentration as long as it was covered by the high moisture content layer.

Rather than drill numerous borings to attempt to define the lateral extent of the contamination, a decision was made to perform the equivalent of a pilot SVE test and evaluate the initial decay and subsequent rebound to define the volume of contaminated soil, the mass of TCE in this residual source, and the mass transfer coefficient for calculating a mass flux toward the surface. A small, one horsepower regenerative blower powered by a standard single phase, 120V, 20A wall outlet was used for the pilot SVE with GAC for vapor treatment, simplifying the testing.

To analyze the test, a two-region model of SVE developed by Praxis Environmental Technologies and published as Appendix F of the U.S. ACE (2002) SVE and Bioventing Engineers Manual was utilized. The extracted vapor concentration data and the cumulative mass extracted were used to calibrate the two-region SVE model. The two-region model of SVE provides an estimate for the residual mass and quantifies mass transfer constraints. In short, the model volume-averages vapor concentrations over the contaminated soil volume (conceptualized as partially mobile/advective and partially immobile/diffusive) and is based on an overall mass balance.

The results of the field testing and data evaluation were:

- The characteristic volume of contaminated soil was estimated to be 2,700 yd<sup>3</sup>
- The bulk mass transfer coefficient between soil types was estimated to be 0.0854 day<sup>-1</sup>
- Estimated initial mass of TCE within the influence of extraction was 13.4 lbs
- Estimated mass of TCE extracted during the testing was 12.6 lbs
- 3 days of initial extraction removed 40% of the original TCE mass

- 57 days of additional extraction removed 54% of the original TCE mass
- 6% of the original TCE mass remained after testing
- Estimated residual mass of TCE of about 0.8 lbs
- At the end of the extraction testing, the TCE mass removal rate was 0.03 lbs/day
- Maximum theoretical vapor concentration remaining in the small low permeability source soils is 35 ppmv. reduced from an initial measured concentration over 600 ppmv, a 95% reduction after 77 days including 60 days of active SVE.

In summary, years of SVE at this site extracted more than 1,600 lbs of SVE; yet, a residual mass of about 13 lbs in a clayey silt layer required additional SVE to complete the cleanup after the moisture content at the site decreased.

## **9.2 Case Study #2: Evaluation of Mass Transfer across the Capillary Fringe from SVE Operational Data**

In the second case study, SVE was applied in a single groundwater monitoring well with 20 ft of screen exposed to the bottom of the vadose zone as a result of a falling table over the past 20 years, making the well amenable to SVE. The well was about 500 ft downgradient from the original source area of TCE releases and appeared to reside near the centerline of the resulting dissolved TCE groundwater plume. The action provided an assessment for the potential mass extraction rate of contaminant volatilized from contaminated groundwater and the use of SVE to mitigate vapor intrusion from contaminated groundwater.

SVE operated at well MW-07 from November 30, 2011 until March 18, 2014, with an average gas extraction rate of about 200 scfm. The purpose was to assess the benefits of TCE mass removal from underlying groundwater and surrounding vadose zone soils. The total mass of TCE extracted from the well

was estimated to be 322 lbs during the initial 20-month extraction period with an initial rate of 1.4 lbs/day and a final rate of about 0.22 lbs/day.

A conceptual model for contaminant mass available for vapor extraction around the well consists of dissolved mass transported with groundwater from the original source zone that subsequently volatilized and diffused upward. The available mass for upward diffusion increased as the water table fell, leaving soil partially saturated with immobile contaminated water (formerly groundwater) at the bottom of the vadose zone. In addition, a relatively low permeability unit in the middle of the vadose zone acted as a cap that constrains the rate of diffusion upward to the surface.

Straightforward two-domain modeling as described in Section 5.2, modified to include contaminated groundwater as source for extracted mass, was matched to the extracted vapor concentration history and mass extraction to assess the activity. The total mass of TCE extracted was about 320 lbs and exceeded the estimate of 234 lbs for the initial mass in the vadose zone. The balance was the result of TCE volatilization from contaminated groundwater over a large area after sweeping the permeable soils and creating a driving concentration gradient. At the end of the extraction in March 2014, the mass extraction rate was nearing a balance with the volatilization rate from groundwater at a rate of about 0.16 lbs/day and an estimated 117 lbs of TCE was volatilized from underlying groundwater and extracted during the 20 months of extraction. Restart of the extraction in November 2015 after a 20-month rebound period and subsequent operation through April 2016 yielded an additional 45 lbs of TCE.

The data fit yielded a bulk (volumetric) mass transfer coefficient for volatilization across the capillary fringe of  $0.0002 \text{ day}^{-1}$  with an average groundwater TCE concentration of  $1,400 \mu\text{g/L}$ . These values, assuming the average groundwater concentration is constantly recharged, yield an asymptotic TCE vapor extraction mass rate of about 0.15 lbs/day. Hence, over a longer-term steady operation, vapor extraction is

expected to level off at about 0.15 lbs/day, with underlying groundwater as the source that is somewhat independent of the extraction rate if the extracted concentration is maintained at a low value compared to the groundwater concentration.

Design of additional SVE or pulsing can be based on the extraction rate or exchange rate in an effort to balance the mass transfer processes. Consider the governing equation for the extracted concentration provided in Section 5.2,

$$\begin{aligned} & [\phi_a(1 - S_a)F_aR_a] \frac{d\bar{C}_a^g}{dt} \\ &= -\frac{Q}{V_t} \bar{C}_a^g + \alpha_d(\bar{C}_d^g - \bar{C}_a^g) \\ &+ \alpha_{gw}(H\bar{C}_{gw}^w - \bar{C}_a^g) \end{aligned}$$

Scaling arguments yield estimates for extraction rates by comparing the extraction term with the groundwater volatilization while neglecting the faster mobile/immobile domain mass transfer,

$$\begin{aligned} \frac{Q}{V_t} \bar{C}_a^g &\gg \alpha_{gw}(H\bar{C}_{gw}^w - \bar{C}_a^g) \\ Q &\gg \alpha_{gw} V_t \left( \frac{H\bar{C}_{gw}^w - \bar{C}_a^g}{\bar{C}_a^g} \right) \sim \\ &\alpha_{gw} V_t (10 - 1) \sim 9 \alpha_{gw} V_t \\ Q &\gg 9 (0.0002 \text{ day}^{-1}) (650,000 \text{ m}^3) \\ &= 1,100 \frac{\text{m}^3}{\text{day}} = 29 \text{ scfm} \end{aligned}$$

In this estimate, the driving concentration gradient for mass transfer was assumed to be held at 90% of the maximum ( $C_{\text{extract}} \sim 17 \text{ mg/m}^3$ ) and yielded an extraction rate significantly lower than the flow sustained during the extraction test.

This first order estimate suggests an extraction rate as low as 30 scfm may be sufficient to keep concentrations low over a large area and could be used to mitigate vapor intrusion for buildings on the surface. The low extraction rate is a direct result of the low volatilization rate from groundwater. The

estimated bulk mass transfer coefficient between groundwater and the bottom of the vadose zone is  $0.0002 \text{ day}^{-1}$  and suggests a re-equilibration timescale of about 10 years. These results have implications for designing low-level SVE to mitigate vapor intrusion by preventing contaminant mass from diffusing upward toward the surface. The testing described in this case study has applicability for design at any site where contaminated groundwater is a potential source for vapor intrusion.

In a current EPA research effort to assess vapor intrusion mitigation with SVE (Lutes et al., 2017; Schumacher et al., 2017, Truesdale et al., 2016), this same interaction between contaminated groundwater and mass extracted during SVE is being studied to develop field test methods for quantifying the mass flux potential from contaminated groundwater as the source for vapor intrusion.

## 10 ACKNOWLEDGEMENTS

This Engineering Issue Paper was prepared for the U.S. EPA Office of Research and Development (ORD), National Risk Management Research Laboratory (NRMRL) by RTI International under Contract No. EP-C-11-036, Task Order 025. John McKernan served as the EPA Task Order Manager. Ed Barth of EPA's ORD NRMRL, served as EPA's technical lead. Robert Truesdale managed and technically directed this work and Dr. Lloyd "Bo" Stewart of PRAXIS Environmental Technologies was the primary author and technical lead. Jennifer Redmon provided technical input to an earlier version of the document, and Coleen Norheim was the RTI Contract Manager.

This EIP is intended as an overview of SVE for EPA staff, regional program offices, RPMs, and state governmental environmental staff. Because SVE is an evolving remediation technology, interested parties can further consult the body of literature and experience that constitutes the state-of-the-science for SVE treatment. As of the date of this publication, questions may be addressed to Mr. McKernan or

Mr. Barth, EPA ORD NRMRL  
([mckernan.john@epa.gov](mailto:mckernan.john@epa.gov), 513-569-7415;  
[barth.ed@epa.gov](mailto:barth.ed@epa.gov), 513-569-7669).

For additional information, please contact:

John McKernan, Director  
U.S. EPA ORD Engineering Technical Support  
Center (ETSC)  
26 W. Martin Luther King Drive MLK-489  
Cincinnati, OH 45268  
513-569-7415  
[mckernan.john@epa.gov](mailto:mckernan.john@epa.gov)

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## Appendix A.

### Case Study #1, Assessment of a Small Persistent TCE Source

#### A.1 Background

Site 32 is in California and includes facilities for aircraft maintenance and repair. Historical activities at Site 32 and adjacent sites have resulted in soil, soil gas, and groundwater contamination. Historical operations included use and storage of trichloroethylene (TCE). Infrastructure of interest at Site 32 includes 2 underground storage tanks (USTs) containing TCE that were removed in 1997, 13 former oil/water separators (OWSs) subsequently removed, 2 vehicle wash racks, and 1 aircraft wash pad. To address soil gas contamination at Site 32, a soil vapor extraction (SVE) system was installed and began operation in April 1998. The system consisted of two vapor extraction wells (VE 2 and VE 3) and five nested vapor monitoring points. The conceptual site model, circa 1999, is illustrated in **Figure A-1**. Until the year 2000, when two OWSs were removed and VE 4 was installed, the SVE system operated inefficiently with a stagnation zone located within a source zone and pulled mass from a stronger, unidentified source zone associated with the two OWSs as illustrated in **Figure A-1**. Despite these limitations, the system removed more than 1,000 lbs of TCE.

The expanded SVE system was operated until 2008 with a total of five rebound periods spaced throughout the operating period. The number of wells operated was reduced and the operations changed to pulsing in 2009 when rebound concentrations were below cleanup goals in all locations except the shallow screen of VE 4. The extracted TCE concentration history at the system manifold and the cumulative TCE mass removed are plotted in **Figures A-2** and **A-3**, respectively. As shown in **Figure A-2**, the extracted TCE concentration dropped below the maximum contaminant level (MCL)-equivalent vapor

concentration of 350 ppbv in 2007, more than two orders of magnitude below the initial concentration of about 100 ppmv. The concentration decay resulted in a diminishing mass extraction rate as illustrated in **Figure A-3** for the cumulative mass removed. The addition of VE 4 in 2000 generated most of the mass of TCE extracted after that date. Extraction at this location eliminated the migration of TCE from this area toward VE 2 and reduced the mass extraction rate from VE 2. A decision to pursue permanent shutdown of the SVE system was made in 2009 based on the low volatile organic compound (VOC) concentrations in rebound soil gas samples, very low mass removal rates, and escalating cost per pound of VOCs removed. All extraction was ceased in June 2009 and the SVE system was later dismantled.

Initial review of the SVE data and quarterly monitoring of vapor concentrations through 2014 suggested the site could be closed. However, California experienced an extended period of drought-like conditions starting in 2013 and the moisture content in the shallow vadose zone at Site 32 began to decrease. A soil gas sampling event in early 2014 in the shallow screen of VE 4 yielded a TCE concentration more than an order of magnitude over the previous quarter and the regulatory community rescinded a previous verbal agreement to close the site pending an assessment of the remaining source mass.

A review of the historical boring log for VE 4 and soil sampling for physical analyses indicated a clayey silt interval existed at VE 4 from a depth of about 25 to 35 ft below ground and likely created some degree of perched water at 25 ft. The lateral extent of such water was not known. The conceptual site model was revised to account for this water and its disappearance during the drought conditions exposing the interface of the clayey silt to overlying silty sand. In effect, the

barrier to volatilization was removed. The contamination in the clayey silt was the result of

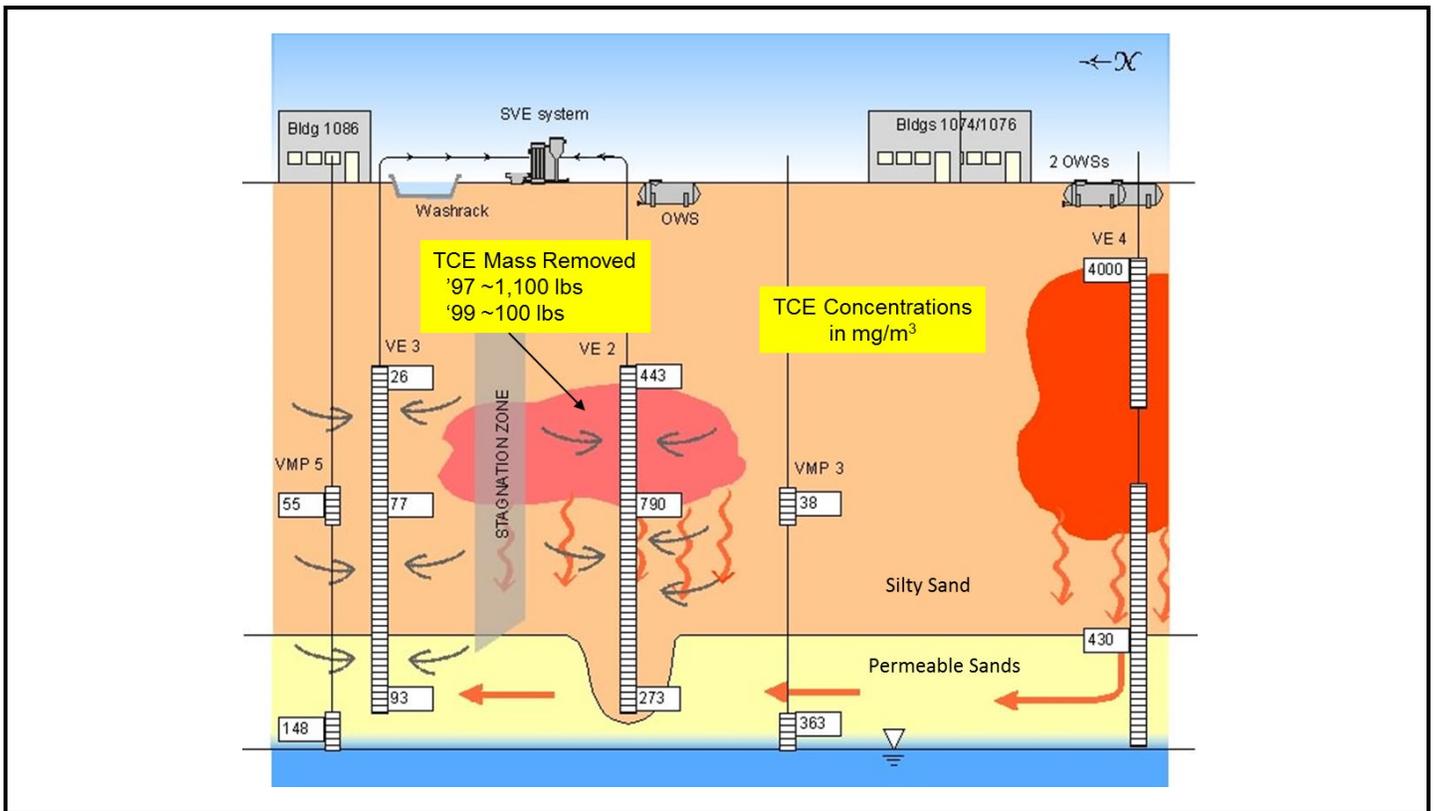


Figure A-1. Conceptual Site Model of Site 32 in 1999

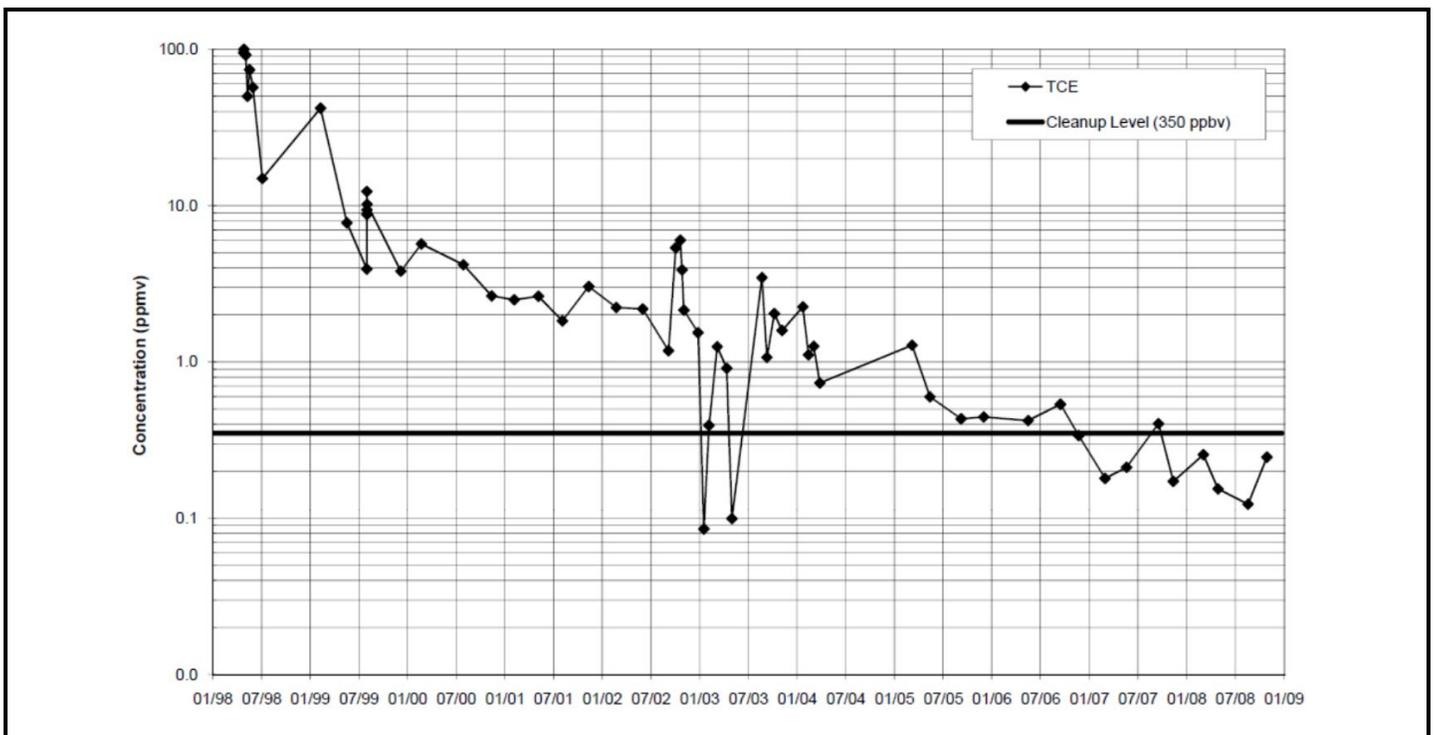


Figure A-2. Extracted soil gas TCE concentration history, Site 32

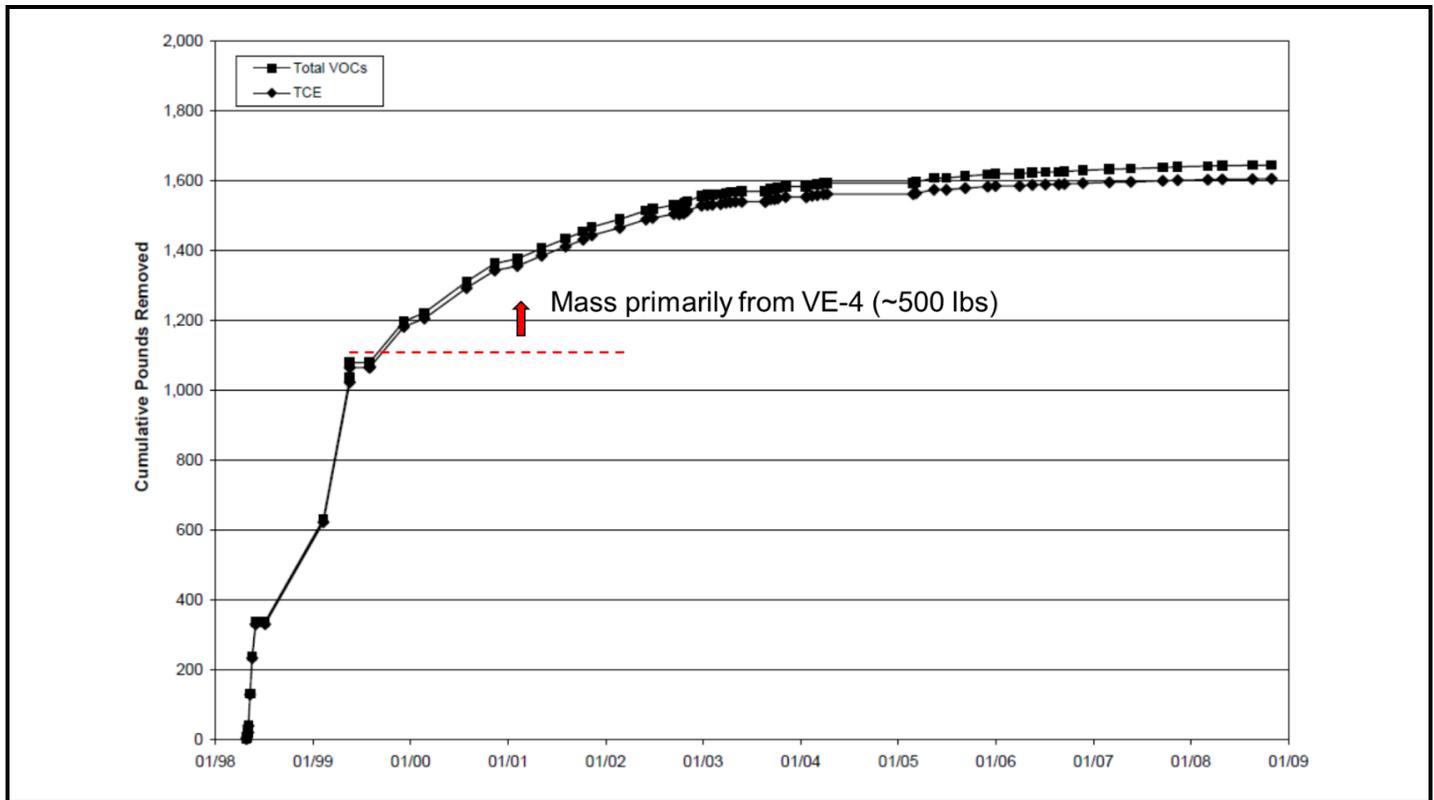


Figure A-3 Cumulative Contaminant Mass Extracted, Site 32

overflow and leaks of TCE-laden water from the OWSs that migrated downward and seeped into this fine-grained interval and remained relatively pristine while covered by a layer of high moisture content.

## A.2 Field Test and Data Collection

Rather than drill a large number of borings to attempt to define the lateral extent of the contamination, the equivalent of a pilot vapor extraction test was performed and initial decay and subsequent rebound were evaluated to define the volume of contaminated soil, the mass of TCE in this residual source, and the mass transfer coefficient for calculating a mass flux toward the surface. A small, 1 horsepower regenerative blower powered by a standard single phase, 120V, 20A wall outlet was used for the extraction in the shallow interval of VE 4, screened from 10 to 30 ft below the surface. Extracted vapors were routed through granulated activated carbon (GAC) prior to atmospheric discharge. The testing was performed in four phases:

- Soil vapor extraction from October 1, 2014 to October 4, 2014 (Phase I extraction)
- Rebound from October 4, 2014 to October 21, 2014
- Soil vapor extraction from October 21, 2014 to December 17, 2014 (Phase II extraction)
- Rebound from December 17, 2014 to January 21, 2015.

The rebound following the Phase II extraction included a 6-hour extraction on January 14, 2015 at well VE 4s with the collection and analyses of soil gas samples for comparison with the previous extraction periods following rebound.

SVE was not conducted at VE 4s between June 2009 and October 2014. It is assumed this long period of dormancy before starting the mass transfer testing allowed the site to re-equilibrate fully to ambient conditions. A plot of the TCE vapor concentrations measured in VE 4s as a function of the elapsed days from the start of extraction is provided in **Figure A-**

4. The concentration is plotted on a log scale to illustrate the rapid initial decay associated with sweeping vapors from the permeable soils followed by a second, slower decay associated with mass transfer limitations during the longer extraction period of Phase II. These two trends are described in more detail in the next section.

Comparing the initial TCE concentration in **Figure A-4** of about 600 ppmv with the historical concentrations plotted in **Figure A-2** demonstrates the TCE concentration in 2014 was higher than that measured before years of SVE at the site (~100 ppmv). Clearly the high moisture content atop the clayey silt interval effectively sequestered the dissolved TCE at the top of this interval. Comparing the peak TCE concentration and decay during Phase I extraction with that in Phase II reveals a rebound in concentration between the two phases and a decreased peak value. This behavior is repeated between the Phase II extraction and the 6-hour sampling event for rebound. In addition, the longer period of extraction in Phase II yielded a much lower peak TCE concentration for rebound that was more than an order of magnitude less than the Phase I peak. These observed trends display the classic decay and rebound expected from the operation of SVE when a significant fraction of the TCE mass is removed from the soils.

The calculated cumulative TCE mass extracted through VE 4s is plotted in **Figure A-5**. At the end of the 3-day extraction in Phase I, the trend in the cumulative mass extracted from VE 4s was clearly increasing and led to the decision to implement the longer-term Phase II extraction. The initial extraction rate in VE 4s during Phase II was lower than Phase I and the lesser rate is evident in **Figure A-5**. After the rate was increased and over time, the mass extraction rate from VE 4s approached an asymptote. At the end of the Phase II extraction, the TCE mass

extraction rate was only 0.03 lbs/day. As indicated, the total mass extracted was about 12.6 lbs.

### A.3 Data Evaluation and Implications

To analyze the classic scenario of this test, a two-region model of SVE developed by Praxis Environmental Technologies and published as Appendix F of the U.S. Army Corps of Engineers SVE and Bioventing Engineers Manual is available.<sup>4</sup> The vapor concentration data illustrated in **Figure A-4** and the cumulative mass extracted illustrated in **Figure A-5** at VE 4s were used to calibrate the two-region SVE model. Application of the model to this testing is illustrated conceptually in **Figure A-6**.

The two-region model of SVE provides an estimate for the residual mass, quantifies mass transfer constraints, and evaluates possible future extraction strategies. In short, the model volume-averages vapor concentrations over the contaminated soil volume (conceptualized as partially mobile/advective and partially immobile/diffusive) and is based on an overall mass balance. The following parameters are assumed measured or otherwise available and employed as input data by the model:

- $b$  (m), depth interval of the contaminated soil volume
- $T$  (K), soil temperature
- $H$  (kPa m<sup>3</sup>/mol), Henry's constant
- $K_{d,m}$  (L/kg), the distribution coefficient in mobile region
- $K_{d,i}$  (L/kg), distribution coefficient in the immobile region
- $D_c$  (m<sup>2</sup>/day), pure component free air diffusion coefficient for TCE
- $\varphi_m$ , porosity of mobile region
- $\varphi_i$ , porosity of immobile region

<sup>4</sup> Reference: U.S. Army Corps of Engineers, 2002. Engineering and Design: Soil Vapor Extraction and Bioventing. EM 1110-1-4001.

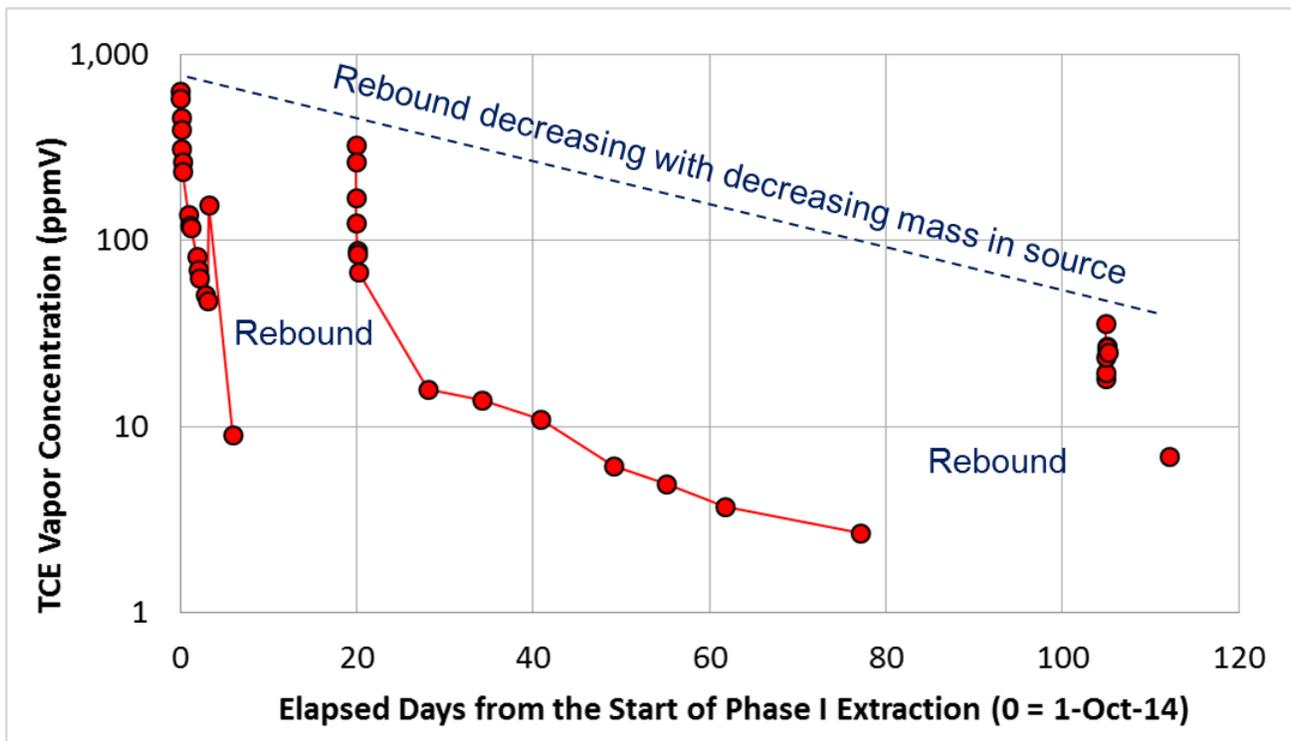


Figure A-4. TCE vapor concentrations in extraction well VE 4s, Site 32

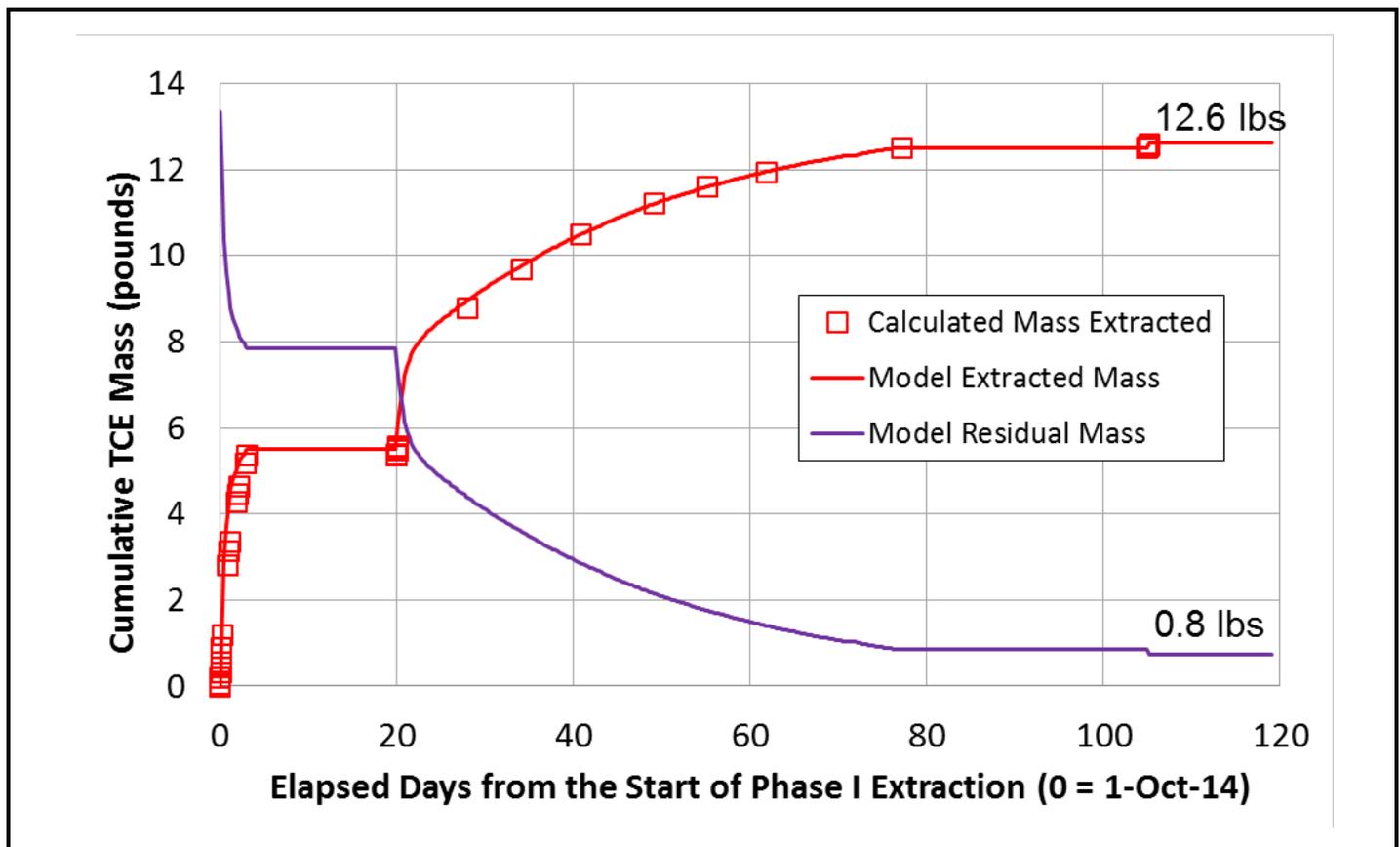


Figure A-5. Cumulative TCE mass extracted from well VE 4s, Site 32

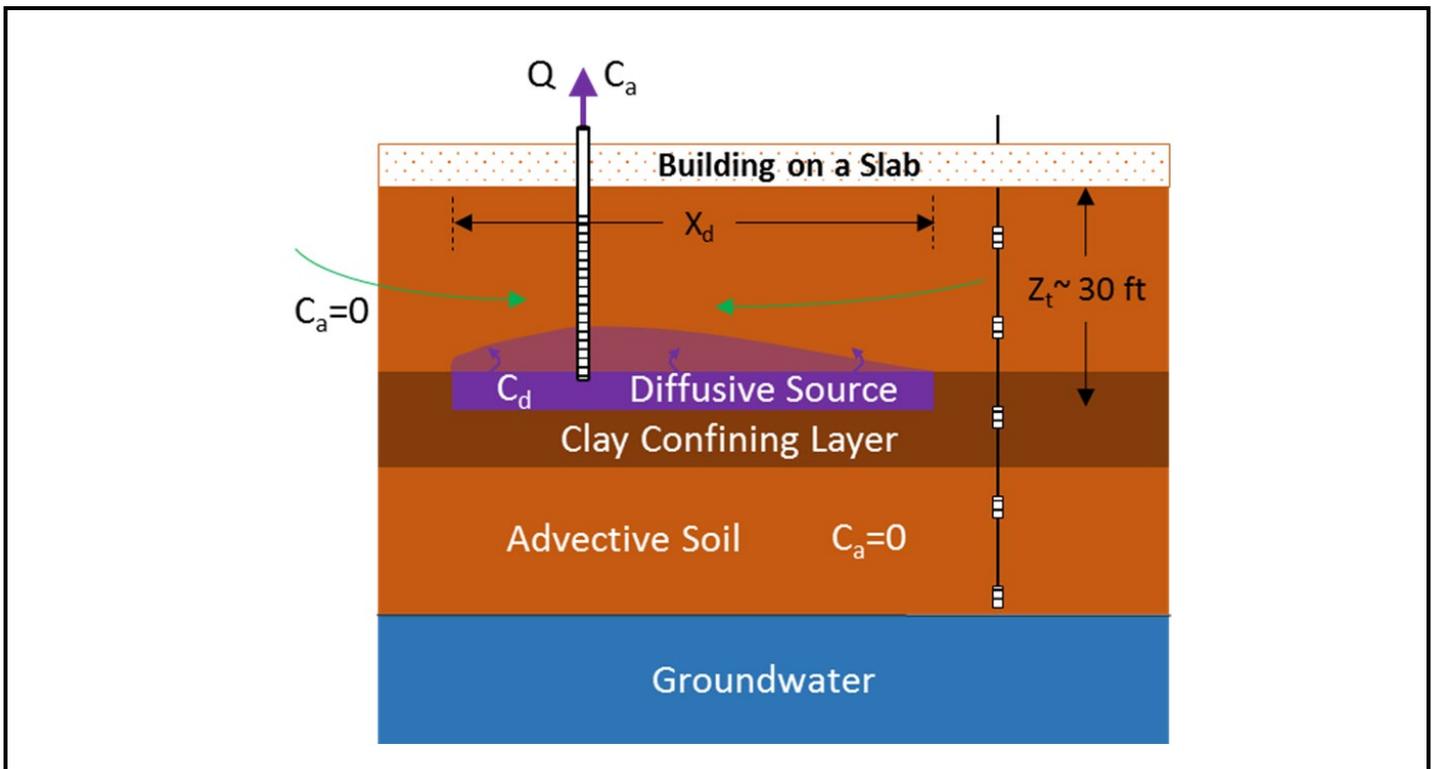


Figure A-6. Conceptual model of extraction from well VE 4s, Site 32

- $\rho_m$  ( $\text{g}/\text{cm}^3$ ), solid density of soil grains in mobile region
- $\rho_i$  ( $\text{g}/\text{cm}^3$ ), solid density of soil grains in immobile region
- $S_m$ , water saturation in the mobile zone
- $S_i$ , water saturation in the immobile zone
- $Q$  (scfm), total soil vapor extraction rate, allowed to be a step-wise transient.

The model is calibrated by varying the following parameters until finding the best match (minimum error) with field measures of extracted vapor concentration and cumulative mass removed:

- $C_{0,m}$  ( $\text{mg}/\text{m}^3$ ), initial vapor concentration in the mobile zone
- $C_{0,i}$  ( $\text{mg}/\text{m}^3$ ), initial vapor concentration in the immobile zone
- $A$  ( $\text{m}^2$ ), equivalent area of soil contamination
- $f_j$ , fraction of the contaminated volume that is characterized as mobile
- $\alpha$  ( $\text{day}^{-1}$ ), bulk mass transfer coefficient between mobile/immobile zones.

In general, if the site has been dormant, the initial mobile and immobile zone concentrations are in equilibrium and are approximated by the early extraction concentration. The area of soil contamination with the depth interval represents the total soil volume used in the volume averaging. The mass transfer constraints for contaminant removal are lumped (averaged) into a bulk mass transfer coefficient,  $\alpha$ . When molecular diffusion alone from fine-grained soils (immobile soils) provides the constraint,  $\alpha$ , is roughly related to diffusion by:

$$\alpha \approx \frac{D_c \phi_i^{4/3} (1 - S_i)^{10/3} \pi^2}{R_i L_i^2}$$

$L_i$  is the characteristic path length for vapor diffusion and  $R_i$  is the vapor retardation coefficient for TCE in the immobile region. The inclusion of the porosity and water saturation in this coefficient represents the tortuosity for diffusion through the soil. The characteristic length is most often correlated with the half-thickness of fine-grained layers such as clays.

Calibration of the model is achieved by finding best fits of the model parameters to the concentration and mass extraction data. Fitting is performed by varying the soil volume, fraction of mobile soil, and mass transfer coefficient in a downhill simplex optimization routine. The fit to the TCE vapor concentrations measured during the mass transfer testing in VE 4s is shown in **Figure A-7**. The model fit to the extracted mass of TCE and the estimated residual mass of TCE remaining in the soil is plotted in **Figure A-5**. The specified soil properties and the resulting best-fit model parameters are listed in **Table A-1**.

Average initial TCE vapor concentrations in both zones were assumed to be in equilibrium at 636 ppmv over a total soil volume of 2,700 yd<sup>3</sup> yielding an initial total mass estimate of 13.4 lbs of TCE in the vadose zone at the start of the mass transfer test. The model fit yielded 40% for the fraction of the vadose zone characterized as mobile, leaving 60% as immobile. Hence, the initial mass of TCE was 5.0 lbs in the mobile soils and 8.4 lbs in the immobile soils. In total, the mass transfer testing removed about 12.6 lbs of TCE, leaving an estimated 0.8 lbs of residual TCE mass as indicated in **Figure A-5**. During the three days of extraction in Phase I, just over 5 lbs of TCE were extracted, which corresponds roughly to the initial mass in the mobile soils and suggesting Phase I provided a single flush of the mobile soil pore volume. Recall, years of SVE extracted over 1,600 lbs of SVE; yet, a residual mass of about 13 lbs required additional extraction to complete the cleanup after the moisture content decreased.

The characteristic volume of contaminated soil was calculated to be 2,700 yd<sup>3</sup>. If the vadose zone thickness is assumed equal to the VE 4s screen length of 20 ft, the effective area was 3,660 ft<sup>2</sup> with a

corresponding circular radius of 34 ft. Using the depth from the ground surface to 30 ft, yields a circular radius of 28 ft. This calculated effective area is much smaller than the original source zone for Site 32 North but consistent with a small residual hot spot.

The bulk mass transfer coefficient of 0.0854 day<sup>-1</sup> is associated with a characteristic diffusion path length of 0.91 ft and indicates a re-equilibration timescale of about 30 days. Vapor retardation coefficients in the mobile and immobile zones were calculated to be 2.6 and 3.6, respectively.

The results of the field testing and data evaluation are in summary:

- Estimated initial mass of TCE within the influence of extraction at VE 4s was 13.4 lbs
- Estimated mass of TCE extracted from VE 4s was 12.6 lbs
- 3 days of extraction in Phase I removed 40% of the original TCE mass
- 57 days of extraction in Phase II removed 54% of the original TCE mass
- 6% of the original TCE mass remains
- Estimated residual mass of TCE proximate to VE 4s was about 0.8 lbs
- At the end of Phase II extraction, the TCE mass removal rate was 0.03 lbs/day and continuing to decline
- Maximum theoretical vapor concentration near VE 4s after mass extraction was 35 ppmv, down from the initial concentration of 635 ppmv, a 95% reduction.

Closure of this site remains under review by regulators.

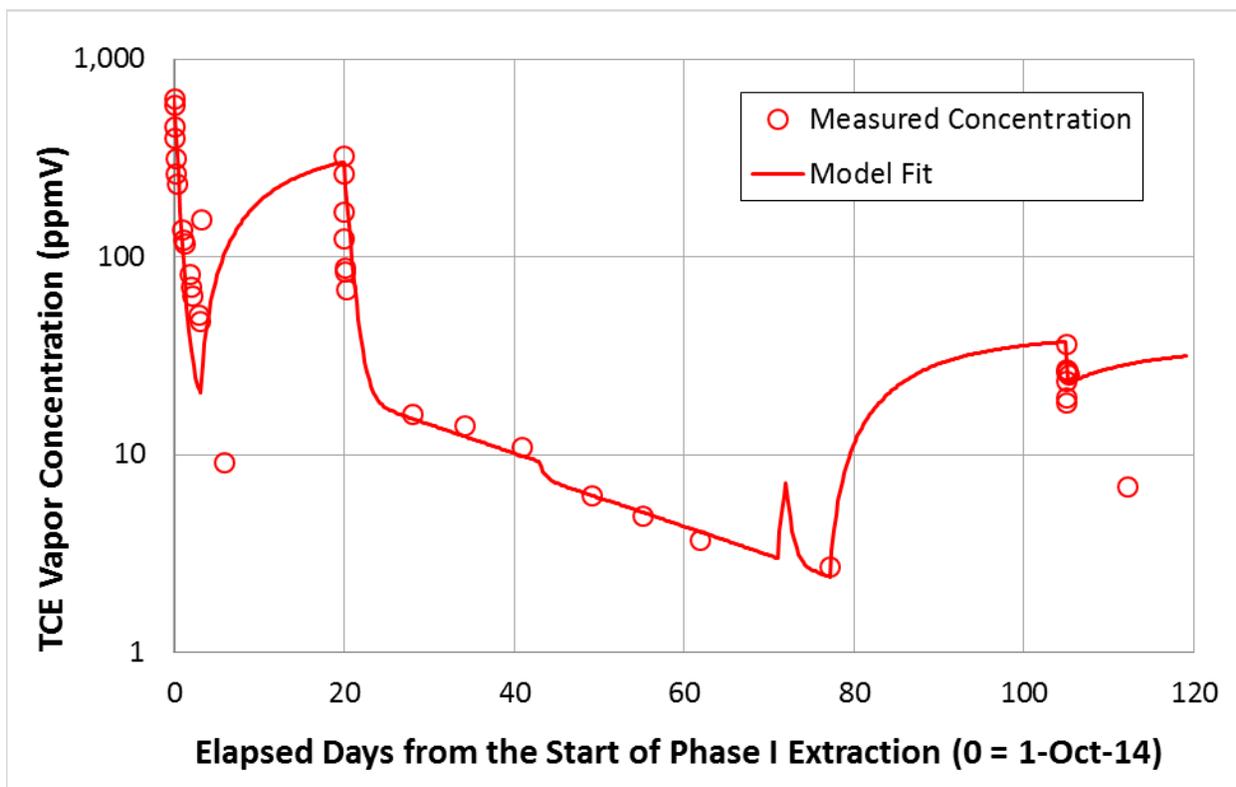


Figure A-7. Model fit to TCE vapor concentrations in well VE4s, Site 32

Table A-1. Parameters for Two-Region Modeling of TCE Extraction from VE 4s

Property	Units <sup>a</sup>	VE 4s
<b>Measured or Assumed Soil Properties</b>		
Porosity, mobile	nd	0.40
Porosity, immobile	nd	0.40
Water Saturation, mobile (vol/vol)	nd	0.25
Water Saturation, immobile (vol/vol)	nd	0.40
Fraction of organic carbon in soil solids ( $f_{oc}$ )	nd	0.0004
$K_d$ , mobile	L/kg	0.05
$K_d$ , immobile	L/kg	0.05
Temperature	°C	20
Initial Vapor Concentration, mobile	ppmv	636

<sup>a</sup> nd = dimensionless

Property	Units <sup>a</sup>	VE 4s
Initial Vapor Concentration, immobile	ppmv	636
<b>TCE Properties</b>		
Henry's Constant	nd	0.38
Octanol-Water Partition Coefficient	nd	200
Diffusion Coefficient in Air	m <sup>2</sup> /day	0.68
<b>Model Best-Fit Parameters</b>		
Effective Volume of Contaminated Soil	m <sup>3</sup>	2,073
Fraction of Soil Characterized as Mobile	nd	0.40
Fraction of Soil Characterized as Immobile	nd	0.60
Bulk Mass Transfer Coefficient	1/day	0.0854

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## Appendix B.

### Case Study #2, Assessment of Mass Transfer across the Capillary Fringe from Contaminated Groundwater to Vadose Zone Soils

#### B.1 Background

At a site contaminated with a chlorinated solvent (trichloroethylene or TCE), soil vapor extraction (SVE) was selected and applied to clean up the contaminated soil. After about 2 years of SVE, rebound monitoring was used to assess the TCE mass volatilized into the vadose zone and to assess the potential mass extraction rate of TCE volatilized from contaminated groundwater. This case study also illustrates the use of pneumatic logging to characterize the permeability of different vadose zone layers of interest to the assessment.

Rebound monitoring was applied in a single groundwater monitoring well (MW-07) with exposed screen at the bottom of the vadose zone. The water table near MW-07 (screened from 77.5 to 127.5 feet below ground surface [ft bgs]) was historically shallower and has fallen about 20 ft over the past 20 years to roughly 97 ft bgs. The deeper water table exposes about 20 ft of the upper screen in MW-07 to unsaturated soils making the well amenable to vapor extraction. MW-07 is located about 500 ft downgradient of the source zone where TCE releases occurred and along the centerline of a dissolved TCE plume emanating from this source zone. Nested soil vapor monitoring probes are near the well.

The conceptual model for contaminant mass available for vapor extraction around this well consists of dissolved mass transported with groundwater from the original source zone that subsequently volatilized and diffused upward, resulting in TCE mass in the vadose zone that has the potential to pose an exposure risk via vapor intrusion. The available mass for upward diffusion increased as the water table fell, leaving soil partially saturated with immobile contaminated water (formerly groundwater) at the

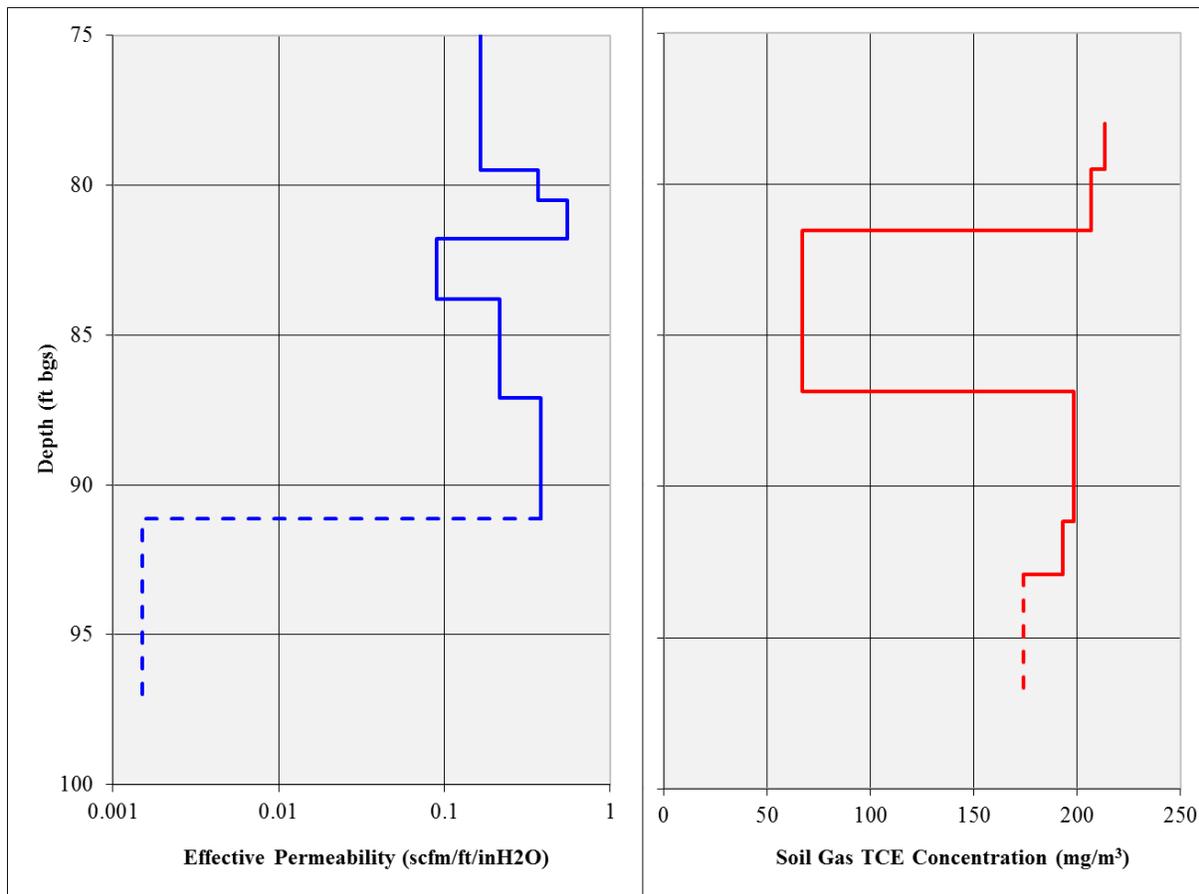
bottom of the vadose zone. In addition, a relatively low permeability unit in the middle of the vadose zone acts as a cap that constrains the rate of TCE diffusion upward to the surface.

SVE operation and rebound testing were performed from 2011 through 2016. The SVE system operated at groundwater monitoring well MW-07 from November 30, 2011 until March 18, 2014 when SVE was terminated to allow the observation of rebound in the vadose zone. Rebound monitoring continued through October 28, 2015 when the SVE system was restarted and continued until April 26, 2016 when SVE was terminated. Monitoring of rebound continues at the site as of the date of this report (December 31, 2016).

#### B.2 Vertical Profiling along the SVE Well Screen

Before starting long-term SVE in MW-07, PneuLog profiles were measured on September 14, 2011. A temporary SVE system operated for 71 minutes to obtain the profiles. Logging was initiated after about 25 minutes of extraction at 90 standard cubic feet per minute (scfm) with an applied vacuum of 17 inches H<sub>2</sub>O. The interpreted vertical profiles for soil permeability to vapor flow and TCE soil vapor concentration are shown in **Figure B-1**.

**Figure B-1** illustrates mostly uniform and permeable soils from above the top of the screen down to a depth of 91 ft bgs with a narrow, less permeable zone from about 81 to 83 ft bgs. The effective permeability suggests the entire screen interval is sandy. No flow was detected below 91 ft bgs down to the water table, although the exact depth of the water table was not measured. Uncertainty in the profiles at the bottom of the well are indicated by the dashed lines.



**Figure B-1.** Effective vapor permeability and interpreted soil gas profiles in MW-07

The measured TCE vapor concentrations were relatively uniform across the screen interval although a vapor sample from 81.5 ft bgs at the transition to a lesser permeable soil was low, suggesting a lesser vapor concentration in the less permeable soils from 81.5 to 87 ft bgs. The permeability of this interval was roughly half that of the adjacent soil layers indicating this layer was not acting as a source of residual TCE mass for the surrounding, more permeable soil. SVE had not been performed in this well other than brief testing and this contributed to the relative uniformity of the vapor concentrations. The vapor sample collected just above the water table yielded a TCE concentration of 174 mg/m<sup>3</sup>. If this vapor sample were in equilibrium with porewater (e.g., the capillary fringe and underlying groundwater), the water concentration would be on the order of 0.45 mg/L.

The geologic log for this well indicates gravel-dominated soil from 75 to 95 ft bgs except for a silty sand from 80 to 85 ft bgs. The PneuLog effective

permeability profile is in general agreement. Below 95 ft bgs, the geologic log recorded mostly silt-dominated soils with some sand intervals down to the bottom of the boring at 135 ft bgs. These observations suggest that a continued decline in the water table is not expected to increase vapor flow from the well as the already exposed gravel intervals will control the flow with little appreciable addition from deeper silty soils. This log also suggests lesser permeable clays and silts provide an upper cap at 45 to 50 ft bgs for SVE applied in the deeper sand and gravel zones.

The falling water table over the past 20 years and the interpreted TCE concentration profile in MW-07 suggest contaminated groundwater was stratified in its transport through the aquifer before the water table declined. Historically, contaminated groundwater likely flowed through sandy gravels above and below the silty sands logged from 80 to 85 ft bgs. During that time, the slow rate of liquid diffusion from gravel

intervals into the silty sands may have left the lesser TCE concentration observed from 81.5 to 87 ft bgs in the PneuLog profile.

### B.3 Field Operations for SVE and Data Collection

SVE was initiated in MW-07 on November 30, 2011 and continued until March 18, 2014. During this operation, vapor concentrations and flows were measured in MW-07 and vapor concentrations were measured in nearby soil vapor monitoring points. The measured vapor concentrations of TCE in vapors extracted from MW-07 are plotted in **Figure B-2**. During the first few months of extraction, the concentration decayed by about two-thirds, from an initial 170 mg/m<sup>3</sup> to roughly 60 mg/m<sup>3</sup>. This range corresponds roughly to the TCE concentrations observed in the PneuLog profile for productive sandy gravels (~200 mg/m<sup>3</sup>) and in the silty sand interval (~60 mg/m<sup>3</sup>). Over the subsequent 20-month extraction period, the concentration decreased at a much slower rate, approaching a decaying asymptote around 20 mg/m<sup>3</sup>.

The calculated cumulative TCE mass extracted through MW-07 is plotted in **Figure B-3**. At the end of the extraction, the trend in the cumulative mass extracted was decaying but significant mass removal continued. The total mass of TCE extracted from MW-07 was estimated to be 320 lbs during the 20-month extraction period with an initial rate of 1.4 lbs/day and a final rate of about 0.22 lbs/day.

### B.4 SVE Data Evaluation

Modeling of the SVE results utilized the two-region model of SVE developed by Praxis Environmental Technologies<sup>5</sup> but the model was modified to include volatilization from contaminated groundwater as a

source for extracted mass. The initial response to SVE in MW-07 is consistent with the two-region model as TCE vapors emanating from contaminated groundwater had decades to diffuse upward and into less permeable (immobile) soils. However, the long-term, asymptotic behavior at MW-07 is consistent with underlying groundwater as a significant source of extracted mass given the lack of other historical sources in the vicinity.

To accommodate contaminated groundwater as a source of extracted mass during SVE at MW-07, the two-region (mobile-immobile) soil model was extended to include mass transfer across the water table as a boundary condition. The expanded model including contaminated groundwater is described in Section 5.2 of the main EIP as represented by

$$R_a \frac{dC_a}{dt} = - \frac{Q}{V_{soil}\phi(1-S)f_a} C_a + \alpha_d \left( \frac{f_d}{f_a} \right) (C_d - C_a) + \alpha_{gw} (HC_{gw} - C_a)$$

The mass transfer coefficient at the interface between the bottom of the vadose zone and groundwater is difficult to predict but can be estimated from SVE operations when contaminated groundwater becomes the primary source of extracted mass. This model formulation is identical to the U.S. Army Corps of Engineers mobile/immobile model if the mass transfer coefficient at the water table is set to zero. The model concept is illustrated in **Figure B-4**. Extracted vapors sweep through more permeable (mobile) soils first yielding a relatively rapid decay in extracted concentration ( $C_m$ ) and then a slow decay in diffusion-limited mass transfer from groundwater.

<sup>5</sup> Published as Appendix F of U.S. ACE (Army Corps of Engineers). 2002. *Engineering and Design: Soil Vapor Extraction and Bioventing*. Engineer Manual EM 1110-1-4001. U.S. ACE, Washington, DC. June 3. <http://www.publications.usace.army>

[http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM\\_1110-1-4001.pdf](http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-1-4001.pdf)

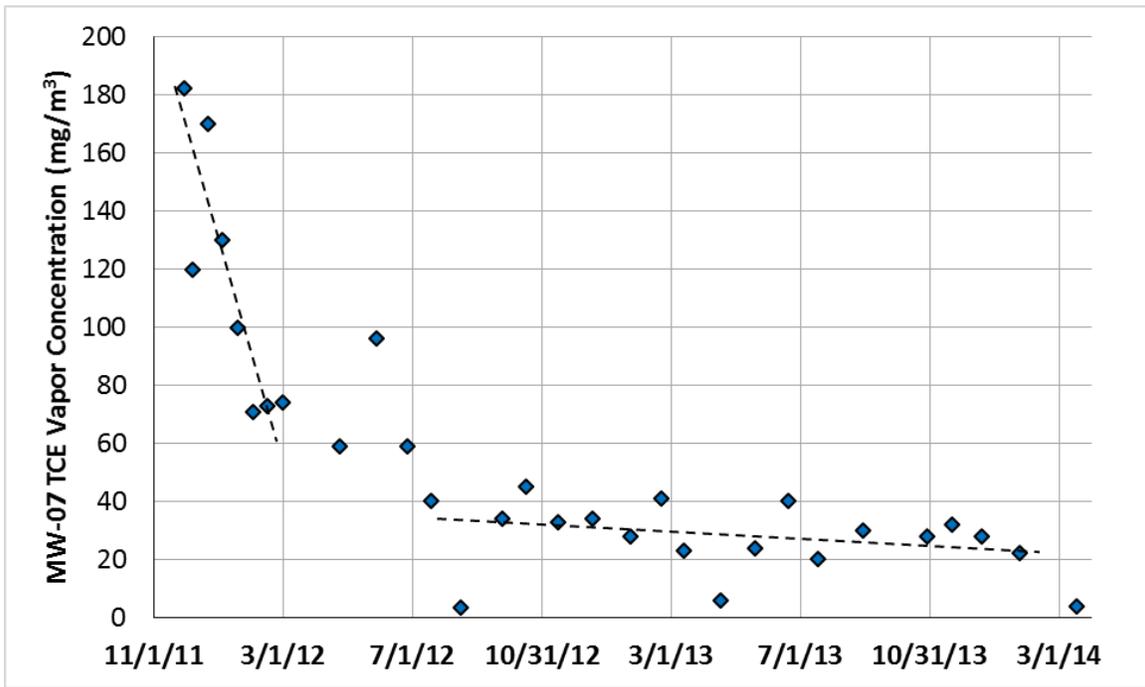


Figure B-2. MW-07 TCE vapor concentrations during SVE

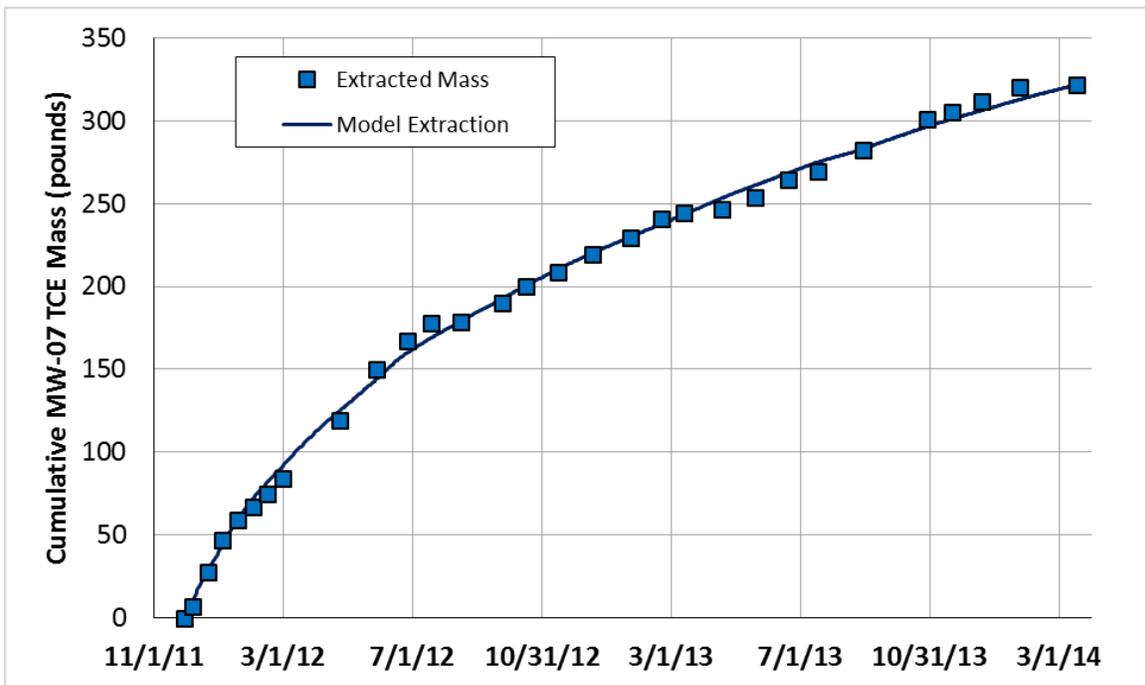
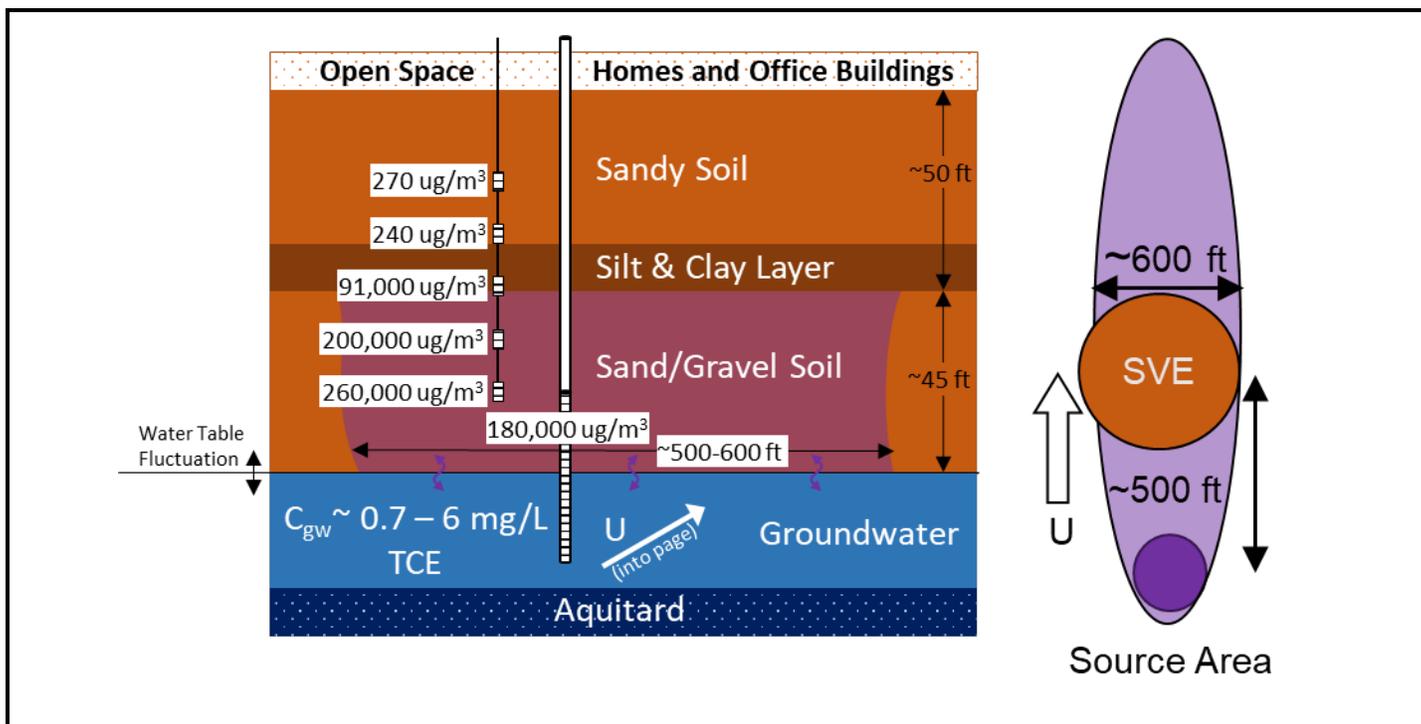


Figure B-3. Cumulative TCE mass extracted from MW-07 during SVE



**Figure B-4.** Conceptual model of extraction from MW-07

The mass transfer characteristics for TCE extracted from MW-07 were estimated initially by fitting the extended SVE two-region model to the measured flow rates and TCE concentration data through March 18, 2014. Additional parameters to include contaminated groundwater as a TCE source are a mass transfer coefficient for volatilization across the water table and the average concentration of TCE dissolved in the groundwater. As described above, the early rapid decay in concentration corresponds to the sweep of the permeable soil volume holding vapors volatilized previously from the groundwater over a long period as well as vapors from residual porewater left by the retreating water table. The subsequent longer decay in concentration is associated with the volatilization of TCE from contaminated groundwater and from porewater in vadose zone soils with high moisture contents. The volatilization rate from groundwater is governed by the mass transfer coefficient, the groundwater TCE concentration, the interfacial area between groundwater and vadose zone, and the vapor extraction rate. The interfacial area is estimated as the volume of impacted vadose zone soil divided by the depth interval of impact in the vadose zone. Based on the geologic log and

concentrations in vapor monitoring points, this interval is assumed to extend from the water table up to the bottom of the confining clays and silts in the middle of the vadose zone (~50 ft = 97 ft bgs to 47 ft bgs) illustrated in **Figure B-4**.

Best fits of the model parameters to the initial extraction and concentration data were achieved using an optimization routine that converged to the fit shown in **Figure B-5**. The specified soil properties and the resulting best-fit parameters including the representative soil volume, initial contaminant concentrations, and volumetric mass transfer coefficients are provided in **Table B-1**.

The fraction of soil characterized as mobile or permeable around MW-07 was 0.56, consistent with the geologic log and PneuLog permeability profile. The groundwater concentration was assumed to be constant during SVE, that is, the extracted mass from the groundwater was considered negligible compared to the total mass in the groundwater traveling through the zone. The average of 10 monthly groundwater samples collected in 2011 before SVE was 2,800  $\mu\text{g/L}$ , and in 2014, after SVE ceased the average was

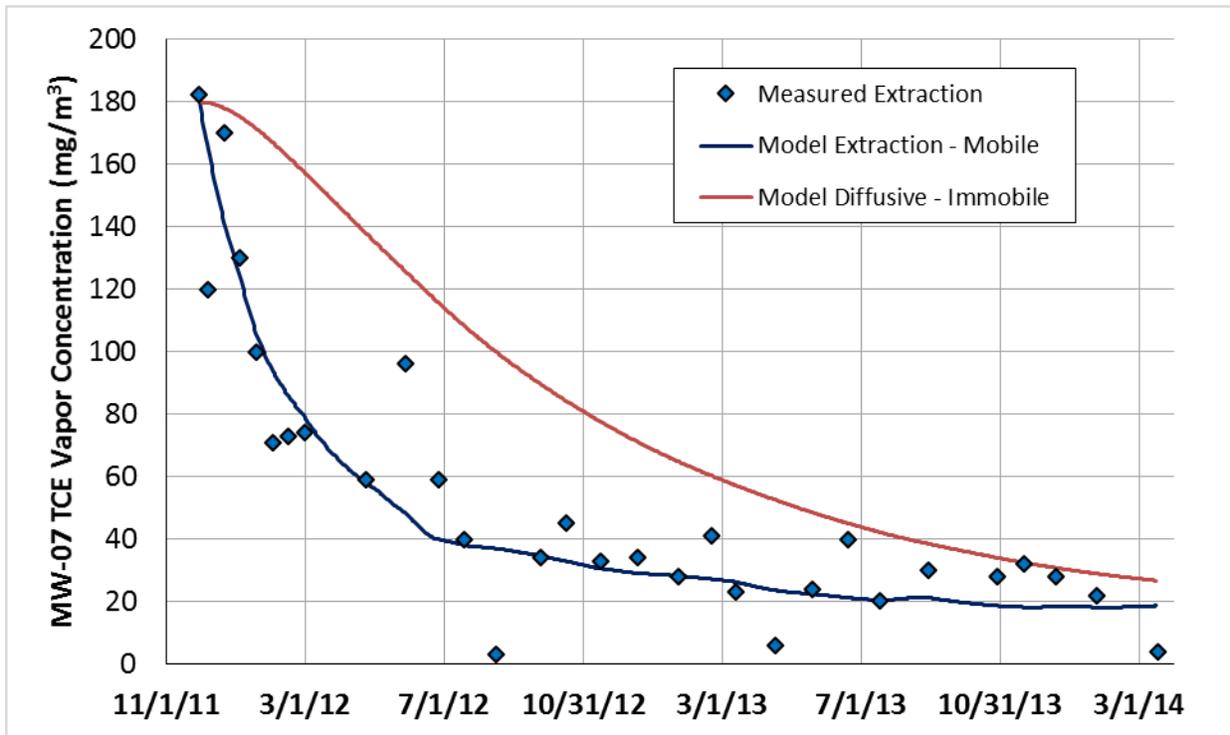


Figure B-5. MW-07 TCE vapor concentrations measured and modeled during extraction

Table B-1. Parameters for Two-Region Modeling of TCE Extraction at MW-07

Property	Units	2011 Source Zone	2014 MW-07
<b>Measured and Assumed Soil Properties</b>			
Porosity, mobile	—	0.45	0.45
Porosity, immobile	—	0.45	0.45
Water Saturation, mobile (vol/vol)	—	0.25	0.25
Water Saturation, immobile (vol/vol)	—	0.40	<b>0.50</b>
K <sub>d</sub> , mobile	L/kg	0.05	0.05
K <sub>d</sub> , immobile	L/kg	0.05	0.05
Temperature	°C	20	20
<b>TCE Properties</b>			
Henry's Constant	—	0.38	
Octanol-Water Partition	—	200	
Diffusion Coefficient in Air	m <sup>2</sup> /day	0.68	
<b>Measured/Assumed TCE Concentrations</b>			
Initial Vapor Concentration, mobile	mg/m <sup>3</sup>	840	<b>180</b>
Initial Vapor Concentration, immobile	mg/m <sup>3</sup>	840	<b>180</b>
Average Groundwater Concentration	µg/L	—	<b>1,400</b>
<b>Model Best-Fit Parameters</b>			
Effective Volume of Contaminated Soil	m <sup>3</sup>	1,221,833	<b>650,000</b>
Fraction of Soil Characterized as Mobile	nd	0.24	<b>0.56</b>
Bulk Mass Transfer Coefficient Mobile/Immobile Soils	1/day	0.00073	<b>0.002</b>
Bulk Mass Transfer Coefficient with Groundwater	1/day	—	<b>0.0002</b>

2,600 µg/L. However, assuming an average groundwater TCE concentration of 2,700 µg/L as the source over-predicted the volatilization rate. A good fit to the data was achieved with a lower groundwater concentration of 1,400 µg/L and indicates the

measured groundwater concentrations may be representative of conditions closer to the bottom of the screen interval.

Average initial TCE vapor concentrations were assessed to be 180 mg/m<sup>3</sup> and in equilibrium between the mobile and immobile soils at the start of extraction. These vapor concentrations are consistent with the values measured during the PneuLog test, the initial vapor extraction in MW-07, and in the deep screens of vapor monitoring points. Hence, the primary fitted parameters are the total vadose zone volume impacted by TCE vapors, the fraction of the volume through which vapors flow (mobile), the mass transfer coefficient between mobile and immobile soils, and the mass transfer between the vadose zone and underlying groundwater. The data fit with the model minimized the difference between measured and modeled extraction concentrations at MW-07 as well as matching the total mass extracted.

The model extracted mass of TCE during SVE in MW-07 is plotted in **Figure B-6** and compared with the calculated mass based on measured concentrations and extraction rates. The model also estimates the initial mass of TCE in the impacted vadose zone surrounding MW-07. Calculated from initial vapor concentrations and soil properties, the estimate was 234 lbs. As indicated, the total mass of TCE extracted was about 320 lbs and exceeded the initial estimate. The balance was the result of TCE volatilization from contaminated groundwater. At the end of the extraction in March 2014, the mass extraction rate was nearing a balance with the volatilization rate from groundwater at a rate of about 0.16 lbs/day and an estimated 117 lbs of TCE had been volatilized and extracted from underlying groundwater leaving about 30 lbs in the vadose zone influenced by SVE in MW-07.

## **B.5 Rebound Data Evaluation**

After vapor extraction was terminated in MW-07 on March 18, 2014, vapor samples were periodically collected and analyzed from MW-07 and surrounding soil vapor monitoring points. This activity continued until vapor extraction was restarted on October 27, 2015 and operated continuously through April 26, 2016. The rebound data are reflective of TCE vapor

concentrations in the vadose zone immediately around MW-07 while the second extraction period provides data directly comparable to the initial extraction effort. The model calibrated to the initial extraction data in the previous section was run to include the subsequent rebound and second extraction periods for validation. During rebound with no extraction, mass transfer between the vadose zone domains and groundwater seek a new equilibrium using the disequilibrium in concentrations at the end of SVE as the initial condition. Similarly, the conditions at the end of the rebound period provide the initial conditions for the second extraction period. TCE vapor concentrations measured during the initial extraction, rebound, and second extraction in MW-07 are plotted in **Figure B-7** along with model forecasts for conditions after March 18, 2014.

The start of the rebound is marked by the upward inflection in the model mobile soil concentration. In general, vapor concentrations in MW-07 decreased immediately after shutdown but then started to increase after a lag period of about 5 months. This concentration was expected to continue climbing slowly with volatilization of TCE from underlying groundwater and was measured to be 83 mg/m<sup>3</sup> at the start of the second extraction period after 20 months of rebound consistent with the model prediction. The lag time of 5 months in rebound may be associated with higher moisture contents found in deeper vadose zone soils above the water table. Notice the model diffusive soil volume acts as a sink for volatilized TCE from the underlying groundwater that enters the permeable soil and diffuses upward throughout the deep vadose zone. The start of the second extraction period is marked in **Figure B-7** by the sudden downward inflection in the extracted TCE concentration on October 27, 2015. The measured concentrations in MW-07 decayed more rapidly than predicted by the model. As described previously, this initial decay during extraction is governed primarily by the volume of permeable soil holding contaminated vapors within the influence of the SVE well. Hence,

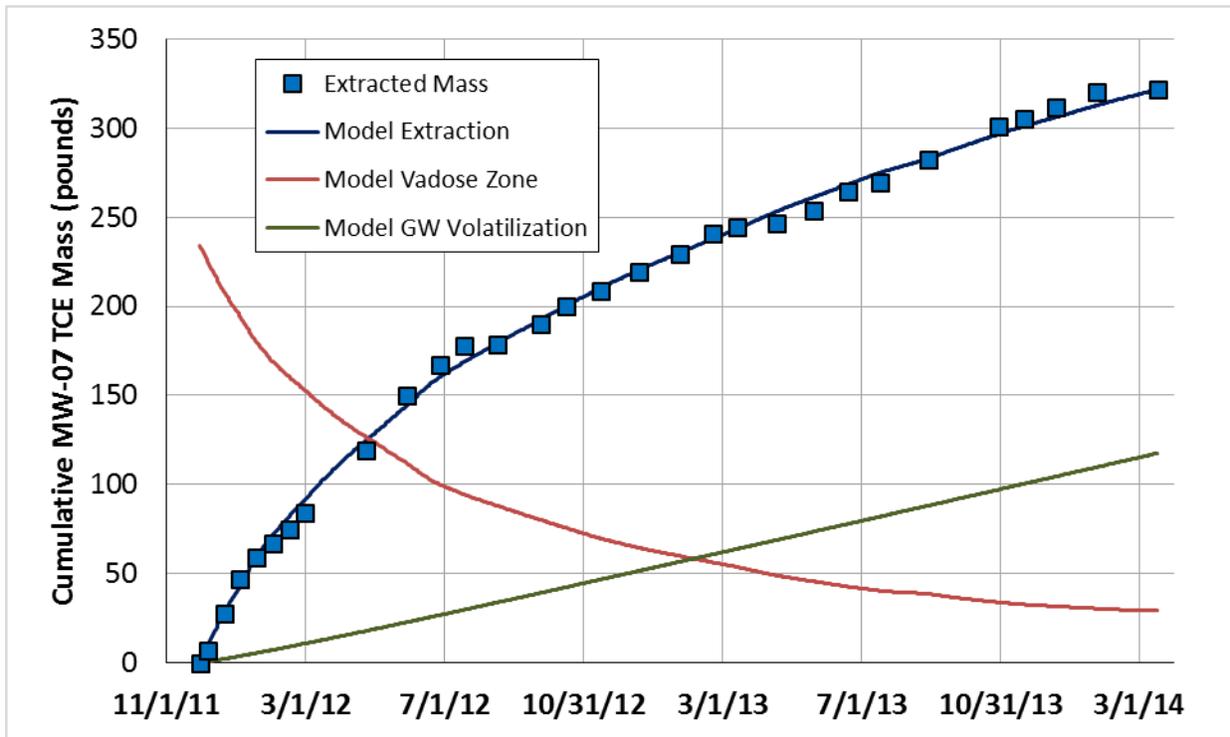


Figure B-6. MW-07 TCE mass extraction and mass balance, Case Study #2

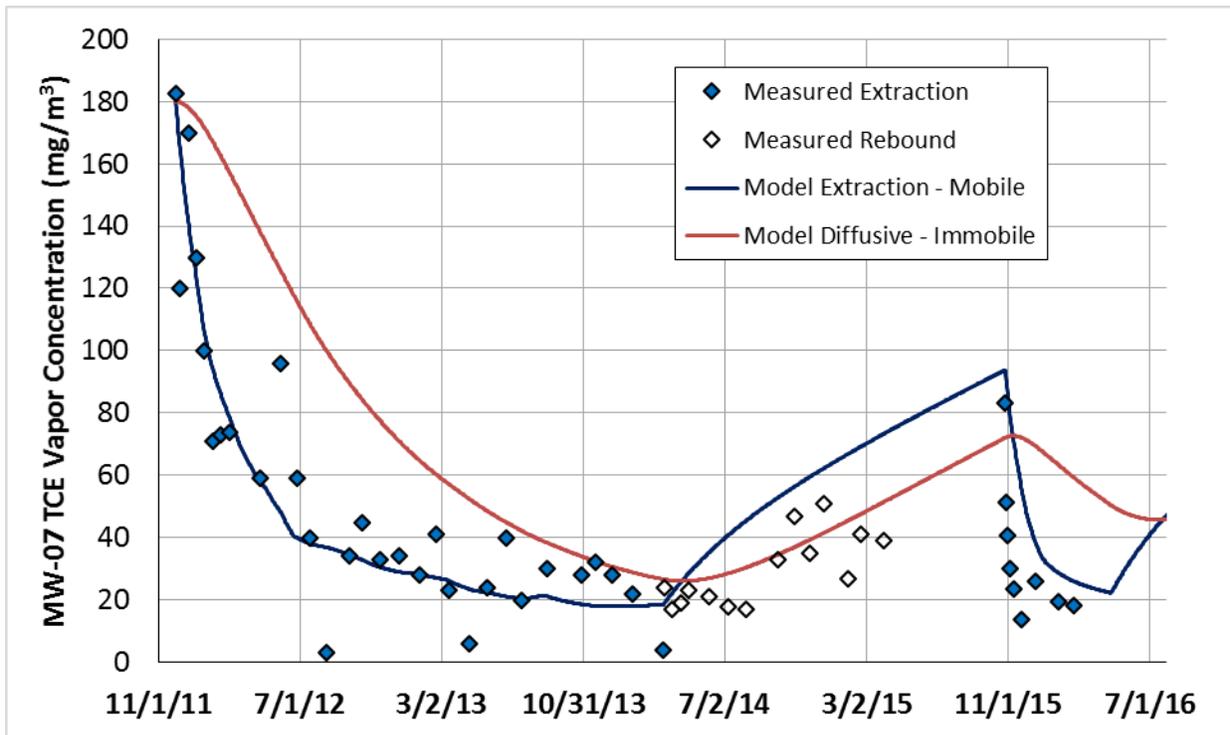


Figure B-7. MW-07 TCE vapor concentrations measured and modeled during rebound

the volume of TCE impacted soil during rebound was less than the original volume. The TCE vapor concentrations measured during extractions and rebound in the three deepest points of nearby soil vapor monitoring point SVM-16 at depths of 56, 68

and 80 ft bgs are plotted in **Figure B-8** along with MW-07 and the model forecast for the mobile soil. The concentrations are plotted on a logarithmic scale to illustrate the trends. All three points in SVM-16 displayed a steep decay with the initial extraction in

MW-07 and remained low. Shortly after ceasing extraction, the shallower depths of 56 ft bgs and 68 ft bgs began to rebound while the deeper point at 80 ft bgs did not show a response until extraction was restarted. All three depths remained at least one order of magnitude below the initial concentrations measured before SVE was started in the more deeply screened MW-07. The low, rapid responses observed at 56 and 68 ft bgs may be influenced by continued mass transfer from the immobile soils or they may reside in more permeable soil (lower moisture content) that communicates more rapidly with the groundwater. All the concentrations are expected to continue climbing slowly without SVE as a result of the slow volatilization of TCE from underlying contaminated groundwater and could approach the initial values of 2011 over decades.

The model mass for TCE in the vadose zone increases during rebound as a result of the volatilization from groundwater as the site seeks a new equilibrium. This increasing mass is indicated in **Figure B-9** and coincides with the increased cumulative mass of TCE volatilized from groundwater during rebound. The volatilized mass entering the vadose zone during rebound was estimated to be 75 lbs or about 0.13 lbs/day. The initial mass in the vadose zone at the start of the second extraction period was modeled to be 108 lbs. The measured and modeled extracted masses of TCE during the post-rebound SVE application in MW-07 are also plotted in **Figure B-9**. As indicated, the measured mass of TCE extracted during the second period was about 45 lbs and was about half of the model estimate of 85 lbs. The discrepancy is the direct result of the measured extraction concentration decaying more rapidly than predicted by the model as was shown in **Figure B-7**. However, toward the end of the extraction in April 2016, the mass extraction rate was approaching the previously observed balance with the volatilization rate from groundwater at a rate of about 0.16 lbs/day.

At the start of the second extraction period on October 27, 2015, the measured concentrations in MW-07 decayed more rapidly than predicted by the model. This initial decay was governed primarily by the volume of permeable soil holding contaminated vapors within the influence of the SVE well. Hence, the volume of TCE impacted soil during rebound was less than the original volume. The lesser volume is the result of incomplete re-equilibration with the underlying groundwater. For the two-domain model, the mobile and immobile domains are somewhat uniformly distributed and the vapor extraction exchanges the pore volume in the mobile domain rapidly. However, the underlying contaminated groundwater is not uniformly distributed but rather lies along one boundary of the domain and therefore its impact is not uniformly observed until near re-equilibration occurs. In other words, only the deeper vadose zone soils above the water table were impacted during the 20-month dormancy, while shallower vadose zone soils originally impacted were not yet equilibrated.

## **B.6 Implications for Future Operation of SVE at MW-07**

Including contaminated groundwater as a source of mass extracted in the vapor phase yields the near asymptotic value in vapor extraction concentration observed in MW-07. The data fit yielded a bulk (volumetric) mass transfer coefficient for volatilization across the capillary fringe of  $0.0002 \text{ day}^{-1}$  with an average groundwater TCE concentration of  $1,400 \text{ }\mu\text{g/L}$ . These values, assuming the average groundwater concentration is constantly recharged, yield an asymptotic TCE mass volatilization rate of about 0.15 lbs/day that is somewhat independent of the extraction rate if the extracted concentration is maintained at a low value compared to the groundwater contamination.

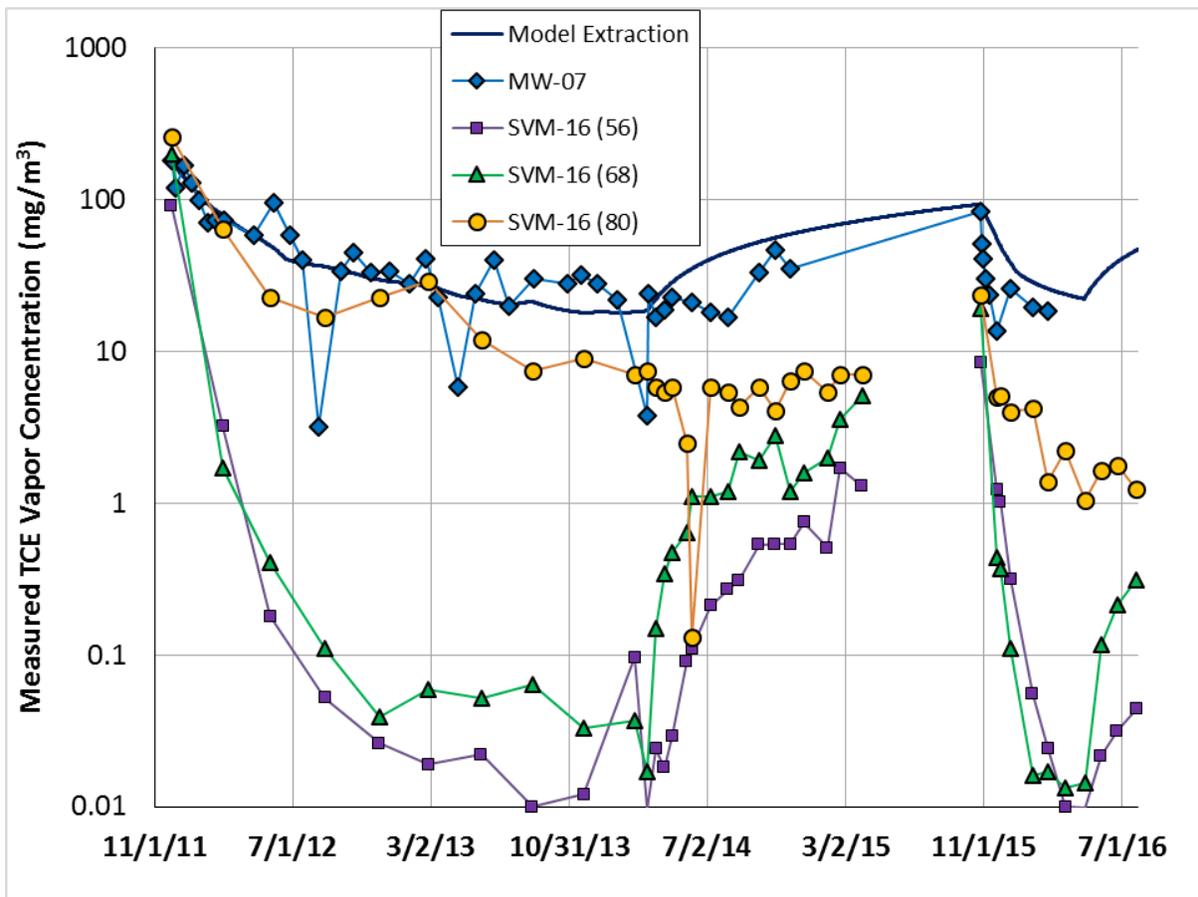


Figure B-8. TCE vapor concentrations measured and modeled during rebound

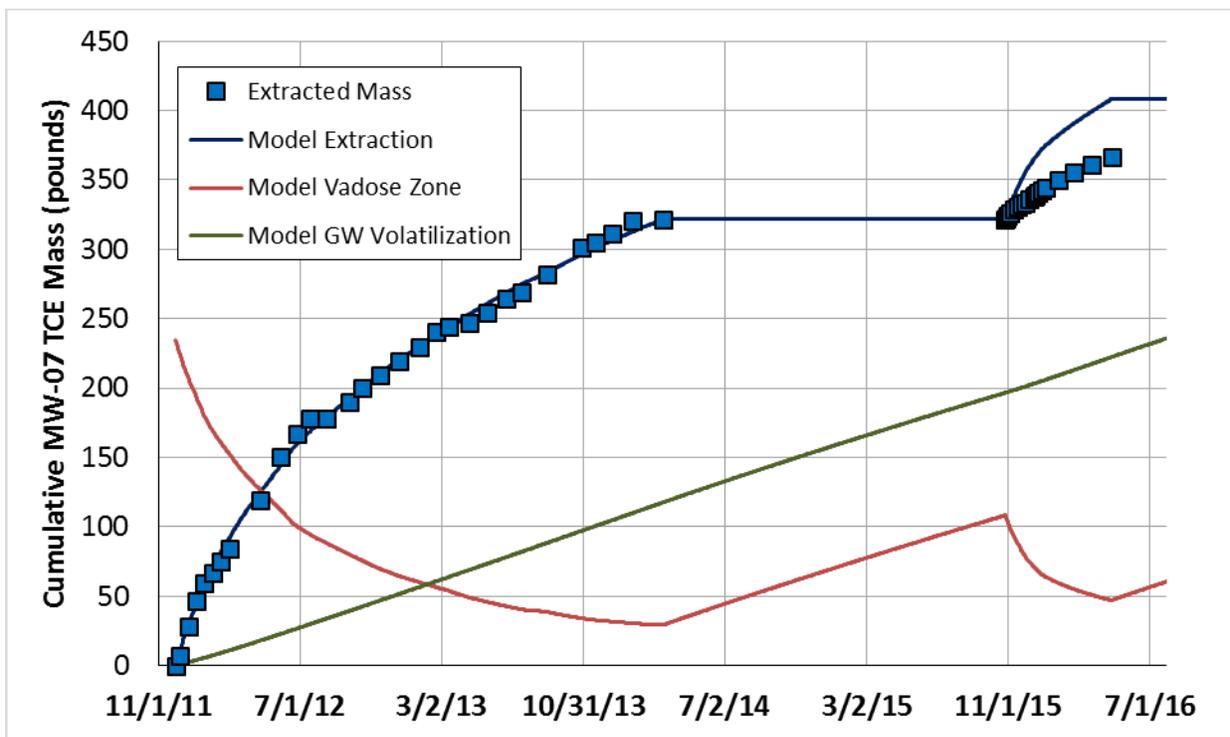


Figure B-9. MW-07 TCE mass extraction and mass balance during rebound

Design of additional SVE or pulsing can be based on the extraction rate or exchange rate in an effort to balance the mass transfer processes. Consider the governing equation for the extracted concentration,

$$\begin{aligned} & [\phi_a(1 - S_a)F_a R_a] \frac{d\bar{C}_a^g}{dt} \\ &= -\frac{Q}{V_t} \bar{C}_a^g + \alpha_d(\bar{C}_d^g - \bar{C}_a^g) \\ &+ \alpha_{gw}(H\bar{C}_{gw}^w - \bar{C}_a^g) \end{aligned}$$

Scaling arguments yield estimates for extraction rates by comparing the extraction term with the groundwater volatilization while neglecting the faster mobile/immobile domain mass transfer,

$$\begin{aligned} \frac{Q}{V_t} \bar{C}_a^g &\gg \alpha_{gw}(H\bar{C}_{gw}^w - \bar{C}_a^g) \\ Q &\gg \alpha_{gw} V_t \left( \frac{H\bar{C}_{gw}^w - \bar{C}_a^g}{\bar{C}_a^g} \right) \sim \alpha_{gw} V_t (10 \\ &- 1) \sim 9 \alpha_{gw} V_t \\ Q &\gg 9 (0.0002 \text{ day}^{-1}) (650,000 \text{ m}^3) \\ &= 1,100 \frac{\text{m}^3}{\text{day}} = 29 \text{ scfm} \end{aligned}$$

In this estimate, the driving concentration gradient for mass transfer was assumed to be held at 90% of the maximum ( $C_{\text{extract}} \sim 17 \text{ mg/m}^3$ ) and yielded an extraction rate significantly lower than the flow sustained during the extraction test.

This first order estimate suggests an extraction rate as low as 30 scfm may be sufficient to keep concentrations low over a large area. The low rate is a direct result of the low volatilization rate from groundwater.

## B.7 Implications for Future Operation of SVE at MW-07

Including contaminated groundwater as a source of mass extracted in the vapor phase yields the near asymptotic value in vapor extraction concentration observed in MW-07. The data fit yielded a bulk

(volumetric) mass transfer coefficient for volatilization across the capillary fringe of  $0.0002 \text{ day}^{-1}$  with an average groundwater TCE concentration of  $1,400 \text{ }\mu\text{g/L}$ . These values, assuming the average groundwater concentration is constantly recharged, yield an asymptotic TCE mass volatilization rate of about 0.15 lbs/day that is somewhat independent of the extraction rate if the extracted concentration is maintained at a low value compared to the groundwater contamination.

Design of additional SVE or pulsing can be based on the extraction rate or exchange rate to balance the mass transfer processes. Consider the governing equation for the extracted concentration provided in Section 5.2,

$$\begin{aligned} & [\phi_a(1 - S_a)F_a R_a] \frac{d\bar{C}_a^g}{dt} \\ &= -\frac{Q}{V_t} \bar{C}_a^g + \alpha_d(\bar{C}_d^g - \bar{C}_a^g) \\ &+ \alpha_{gw}(H\bar{C}_{gw}^w - \bar{C}_a^g) \end{aligned}$$

Scaling arguments yield estimates for extraction rates by comparing the extraction term with the groundwater volatilization while neglecting the faster mobile/immobile domain mass transfer,

$$\begin{aligned} \frac{Q}{V_t} \bar{C}_a^g &\gg \alpha_{gw}(H\bar{C}_{gw}^w - \bar{C}_a^g) \\ Q &\gg \alpha_{gw} V_t \left( \frac{H\bar{C}_{gw}^w - \bar{C}_a^g}{\bar{C}_a^g} \right) \sim \alpha_{gw} V_t (10 \\ &- 1) \sim 9 \alpha_{gw} V_t \\ Q &\gg 9 (0.0002 \text{ day}^{-1}) (650,000 \text{ m}^3) \\ &= 1,100 \frac{\text{m}^3}{\text{day}} = 29 \text{ scfm} \end{aligned}$$

In this estimate, the driving concentration gradient for mass transfer was assumed to be held at 90% of the maximum ( $C_{\text{extract}} \sim 17 \text{ mg/m}^3$ ) and yielded an extraction rate significantly lower than the flow sustained during the extraction test.

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This first order estimate suggests an extraction rate as low as 30 scfm may be sufficient to keep concentrations low over a large area. The low rate is a direct result of the low volatilization rate from groundwater. The estimated bulk mass transfer coefficient of 0.0002 day<sup>-1</sup> suggests a re-equilibration timescale of about 10 years. These results have implications for designing low-level SVE to mitigate vapor intrusion by capturing contaminant mass before it diffuses upward toward the surface. The testing described in this case study has applicability for design at any site where contaminated

groundwater is a potential source for vapor intrusion. For example, even as vadose zone remediation by SVE is terminated, keeping a portion of the infrastructure in place is recommended if groundwater contamination remains. Mitigation of vapor intrusion over a large area encompassing multiple buildings may be as simple as a brief, periodic (e.g., annual) flush of the vadose zone vapor pore volume using a small, portable blower on a well installed previously for SVE (i.e., free for mitigation purposes).

# DESIGN



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