

5.0 SOIL VAPOR EXTRACTION

5.1 Process Description

Soil vapor extraction (SVE) is a commonly-used method for treating soil contaminated with volatile hydrocarbons. The process is sometimes referred to as soil venting, vacuum extraction, aeration, or in-situ volatilization. A closely related remediation technology – bioventing is described in Section 6. In general terms, soil vapor extraction removes volatile organic constituents from contaminated soil by creating sufficient subsurface air flow to strip contaminants from the vadose (unsaturated) zone by volatilization. As the contaminant vapors are removed, they may be vented directly to the atmosphere or controlled in a number of ways.

Soil vapor extraction has been widely used to remediate sites contaminated with gasoline or chlorinated solvents (e.g., TCE). It also is sometimes used to minimize migration of vapors into structures or residential areas during other types of remediation. By its nature, SVE is an on-site, in-situ treatment method.

Complete removal may not be possible unless the source of vapors (e.g., hydrocarbon lens on groundwater) also is removed, so SVE often is used in conjunction with or following other remedial measures such as excavation of subsurface waste bodies, removal (pumping) of any hydrocarbon lens that is present, or air stripping of contaminated ground water. Combined two-phase treatment of both ground water and soil gas has been used successfully for several years (Welshans, et al., 1991), and increasingly is employed.

The success of SVE for a given application depends on numerous factors with the three key criteria being: 1) the nature of the contamination; 2) the behavior of subsurface vapor flow at the site; and 3) regulatory requirements.

Spills or leaks of fuels typically involve liquids containing dozens of different constituents. For removal by SVE to be effective, the contaminants generally must have vapor pressures greater than 1.0 mm Hg at 20°F. A simplified decision guide for judging the applicability of SVE is shown in Figure 5-1.

The tendency of the organic contaminants to partition into water or to be adsorbed onto soil particles also affects SVE effectiveness, so the compound's water solubility, Henry's Law constant, and soil sorption coefficient are of interest. The soil temperature affects each of these variables and hence, the rate of vapor diffusion and transport.

The concentrations of contaminants that are initially present affect their relative partitioning between vapor and liquid phases, and the amount that is solubilized or adsorbed. The time that the contamination has been present also is an important factor, as mixtures of contaminants will generally become depleted of their more volatile components over time through volatilization. This process, referred to as weathering, will tend to cause SVE to become progressively less applicable as the site ages. It also affects the operation of the SVE system, as the more volatile components are typically removed first and the composition of the vapors collected and treated varies over time.

Figure 5-1. Simplified Guide to Applicability of Soil Vapor Extraction.

Source: (Pedersen and Curtis, 1991)

As mentioned above, soil temperature is an important variable in the effectiveness of SVE. Increasing the soil temperature is one option commonly considered for enhancing SVE performance. Soil can be heated in one of three ways: 1) introduction of heated air or steam, 2) input of electromagnetic energy through the soil, or 3) heat release through chemical reaction (HWC, 1994a). The use of heated air or steam appears to be the most widely used approach to full-scale thermally enhanced remediation (HWC, 1992). Approaches such as microwave, radio frequency, and electrical heating have been tested at the pilot scale (George, et al., 1992); (HWC, 1993); and (HWC, 1994b), but full-scale results are not yet available.

Although SVE may be used in a variety of soil types, the effectiveness will depend on the ability of air to flow through the soil. The ability of vapors to flow through a porous media such as soil is usually defined as the air permeability. Any factors that influence the air permeability of the soil, such as soil porosity, grain size, moisture content, depth to ground water, and stratification must be taken into consideration when planning this type of remediation. The presence of cracks, inadequately grouted boreholes, or other subsurface conduits will alter the subsurface flow patterns. The goal is to direct the air flow through the contaminated zone and minimize short-circuiting through bypasses. SVE may not be practical for sites where the source of vapors is deep underground (e.g., >100 feet), in areas with shallow groundwater tables (e.g., <10 feet) or at sites where the groundwater level fluctuates greatly over time. It has been suggested that SVE is not effective for the fraction of organic pollutants that are trapped inside the soil matrix (Travis and Macinnis, 1992).

The types of contaminants present and the clean-up criteria will affect the cost-effectiveness of SVE versus other remediation options. The final cleanup level for contaminants in the soil will dictate whether or not SVE is a viable option. Very stringent cleanup levels may dictate excavation of the soil and further on-site treatment. Air emission regulations may require the use of controls to reduce the level of contaminants in the SVE exhaust gas. The cost of such emission controls may influence the overall selection of a remediation approach.

Figure 5-2 shows a generalized process flow diagram for the SVE process. Typical systems include extraction wells, monitoring wells, air inlet wells, vacuum pumps, vapor treatment devices, vapor/liquid separators, and liquid-phase treatment devices. Wells are generally 4 to 8 inches in diameter. An option sometimes employed is to introduce the air at the air inlet well into the saturated zone (i.e., groundwater table). This technique, referred to as air sparging, acts to strip some of the volatile and semi-volatile compounds from the ground water.

A number of potential problems may arise in implementation of soil vapor extraction, but effective solutions exist for most problems. If there is concern that contaminant vapors from other sources may be drawn in by the vacuum system, air inlet wells may be placed around the perimeter of the site to limit remediation to the site under treatment. To avoid channelized flow, butterfly or ball valves may be placed on the monitoring or extraction wells so that they may be shut down if necessary.

Figure 5-2. Generalized Process Flow Diagram for Soil Vapor Extraction.

The extent of short circuiting through other wells can be determined using a tracer gas (Olschewski, et al., 1995). If contaminated water is extracted in the process, a liquid phase treatment system is usually installed. The oxygen introduced by SVE can promote the growth of iron-utilizing bacteria and lead to decreased pump efficiencies for groundwater extraction; this problem can be minimized by a chlorination program (McCann, et al., 1994).

In bioventing (see Section 6), the rate of vapor extraction is relatively low and the primary objective is to introduce oxygen into the subsurface to promote microbiological activity. This is not the primary goal for SVE, but introduction of oxygen into the subsurface during SVE may, as a side benefit, enhance biodegradation and thereby improve the overall remediation efficiency. Evidence of unusually high carbon dioxide levels indicates that some sites may experience enhanced subsurface biodegradation that may be partially or wholly a result of soil vapor extraction. At one site, carbon dioxide concentrations in the soil gas were 8.5%; much higher than the 0.03% or 0.04% typically present in the atmosphere, though co-disposed municipal waste could have been partially responsible for the high levels. Rough calculations indicated that up to 40% of the gasoline was destroyed by degradation.

The relative advantages of SVE over other remediation approaches are:

- the equipment is readily available and simple to install and operate;
- large volumes of soil can be treated in a cost-effective manner;

- remediation can proceed in many cases without disrupting on-going commercial activities at the site; and
- air emissions are released from a point source and, thus, can readily be controlled.

The major disadvantages of SVE versus other remediation approaches are that:

- The method is not applicable for saturated soils or soils with low air-permeabilities;
- the success of the method varies with the volatility (vapor pressure) of the contaminants present; and
- significant residual contamination may remain in the soil after treatment under some remediation scenarios.

A number of reports and articles have been published that provide useful information regarding SVE systems. The best single source of information is an EPA report (Pedersen and Curtis, 1991). Much of the information in this section was drawn from that report and a second EPA report (Thompson, et al., 1991). Other key references are two studies that include summarized information about existing SVE systems in use at field sites (Hutzler, et al. 1989; and PES, 1989), an evaluation conducted under EPA's SITE program (Michaels, 1989a), and an overview paper (Johnson, et al., 1990). The Johnson, et al., paper is given as Appendix E of this report and EPA's Engineering Bulletin on SVE is contained in Appendix F of this report.

5.2 Identification of Air Emission Points

The air emissions associated with SVE systems come primarily from the stack. Stack heights are typically 10-30 feet and usually only one stack is used (Eklund, et al., 1992a). Additional releases of volatile organics may occur from the treatment of any contaminated water that is extracted. Fugitive emissions are considered negligible due to the negative pressure throughout most of the system.

5.3 Typical Air Emission Species of Concern

Emissions include untreated volatile organics from the extraction process. Removal and emissions of semi-volatile organic compounds will also occur, though with less efficiency than for VOCs. Lesser amounts of air emissions associated with the control system may also occur. Due to the variety of technologies used for vapor treatment, stack emissions may include products of incomplete combustion, NO_x, particulate matter, CO, and acid gases. Of primary concern, however, are the volatile organics emitted from the point sources.

5.4 Summary Of Air Emissions Data

Air emissions data for several SVE systems are summarized in Table 5-1. The data are from a variety of soil vapor extraction systems. Overall, there is little detailed published information about air emissions from SVE systems, making it difficult to assess the representativeness of this sample.

The emission rate of VOC compounds over time from continuously operated SVE systems tends to show an exponential-type decay curve. If the system is stopped and then restarted, however, the VOC emission rate returns to near the

original rate unless the remediation is nearing completion. Shutting off the vacuum allows the soil-gas equilibrium to become re-established. Due to this behavior, the most efficient method of operation often is to run the SVE system only for a part of each day or week, i.e., operate in a "pulsed" mode.

Published emission factors for SVE systems based on typical operating conditions (Thompson, et al., 1991) are:

- Uncontrolled Emissions: 25,000 g/hr or 250 kg/day (based on 10 hours of operation).
- Controlled Emissions: 1,250 g/hr or 0.05 g/g VOC in soil.

5.5 Identification of Applicable Control Technologies

As the vapors are removed from the soil, they are either discharged to the atmosphere or treated to reduce air emissions. Direct combustion is theoretically possible if the hydrocarbon content of the exhaust gas is high enough, but the concentration typically drops significantly during removal. Therefore, natural gas or some other fuel would be needed to maintain combustion. Also, for safety reasons, dilution air typically is added to maintain the VOC concentration below the lower explosive limit (LEL).

For lower levels of hydrocarbons, catalytic oxidation may be effective. Carbon adsorption systems often are used, but they

Table 5-1
Summary of Emissions Data for SVE Systems

Source	No. of Systems Surveyed	Parameter	Units	Range or Value	Approximate Average
Crow (1987)	13	Flow Rate Per Well	cmm (cfm)	0.2-8 (5.3 - 300)	2 (80)
		Removal	kg/day (lb/day)	0.9-113 (2 - 250)	27 (60)
		Exhaust Gas Concentration	ppmv	20 - 350	100
Hutzler, et al. (1989)	19	Total Flow Rate	cmm (cfm)	0.1-161 (3 - 5,700)	23 (800)
		Treatment: - None - Carbon - Catalytic Incineration - Combustion	# systems	9 6 1 1	NA
		Removal Rate	kg/day (lb/day)	2-195 (4 - 430)	45 (100)
PES (1989)	17	Total Flow Rate	cmm (cfm)	0.7-318 (25 - 11,300)	62 (2,200)
		Pollutant Concentration	ppmv	150 - 38,000	4,000
		Control Efficiency	%	90 - 99	95

may be costly to implement and are generally not acceptable for high-humidity gas streams. An EPA survey from the late 1980s indicates that the exhaust from about 50% of SVE systems is vented directly to the atmosphere with no controls (PES, 1989). The trend, however, is for VOC controls to be required. For those systems requiring controls, the most viable options are:

- 1) activated carbon adsorption;
- 2) catalytic oxidation;

- 3) thermal incineration;
- 4) internal combustion engine; and
- 5) miscellaneous control approaches.

The first three treatment options are the most commonly used for large SVE systems such as those used at Superfund sites or refineries. Internal combustion engines (ICE) are a common choice for control of emissions for small systems such as those used at Leaking Underground Storage Tank (LUST) sites. Removal efficiencies of 95-99% for VOCs should be

theoretically achievable with any of these control options.

No single control method is preferred. Each has advantages and disadvantages that must be considered for each specific application. Control options are discussed below. Further information is available from EPA's Technology Transfer and Support Division (TTSD) (Eklund, et al., 1992b).

5.5.1 Carbon Adsorption

Carbon adsorption using GAC is the most common control method for SVE systems. VOCs are removed by being physically trapped on the surface of the GAC or by chemical reactions with the carbon. The efficiency of GAC is due to its very large surface area per unit mass. Two options for GAC systems are available: 1) "throw away" systems, and 2) fixed bed regenerable systems. In the first option, canisters of GAC are used and disposed of or reactivated off-site. In regenerable systems, steam or hot air is used to strip contaminants from the GAC in place. The contaminants are recovered as a liquid. The cost-effectiveness of regenerable systems will increase as the treatment time and the mass of contaminants to be treated increase.

Modular, skid-mounted treatment systems are available from numerous vendors. Prefabricated GAC units containing up to a ton of carbon are available. Flow rates over 1,000 scfm can be accommodated.

The primary advantage of carbon adsorption over other control options is that the control efficiency of GAC systems is not significantly affected by the changes in air flow rate and VOC concentration that

typically occur at SVE sites. It is applicable to most contaminants having molecular weights between 50 and 150; lighter compounds tend to pass through the GAC unadsorbed, and heavier compounds tend to bind permanently to the carbon and cannot be desorbed. GAC tends to be the control method of choice for SVE systems with low VOC concentrations in the exhaust gas (e.g. less than 500-1000 ppmv). Removal efficiencies can exceed 99% under optimal conditions, which include adequate residence time, moderate temperature (100-130°F), and no fouling compounds present in the gas stream.

Carbon adsorption has several limitations that may be significant for SVE applications as shown below. One, water vapor will occupy adsorption-sites and reduce the removal capacity. It is usually recommended that the gas to be treated has a relative humidity of less than 50% for GAC to be effective. Two, carbon tends to not retain organics at temperatures exceeding 150°F. This temperature is well below the temperatures of 200 to 800°F in the exhaust gas that can be caused by compression of offgas in the removal pump. The air can be cooled or pumps used that do not add much heat to the system (e.g., liquid ring seal pumps). Three, high mass loadings of VOCs in the exhaust gas will cause the carbon to be exhausted quickly and result in high costs to replace or regenerate the carbon. The first two limitations can be offset through modifications to the system design, but these modifications will increase the cost of remediation.

5.5.2 Thermal Incineration

Thermal incineration can be used to destroy vapor-phase contaminants. Contaminant-laden vapors are heated to

temperatures above 1000°F via a direct flame or a combustion chamber. The method is applicable to a wide range of compounds and over a large range of concentrations. It is not, however, widely used for SVE applications except for large-scale, long-term cleanups. For the flame to be self-sustaining, the VOC concentration needs to be at percent levels that may be above the lower explosive limit for the contaminant of concern. For lower VOC levels, auxiliary fuel such as methane or propane must be added. The cost of this fuel can be prohibitive. The efficiency of the method is also affected by changes in the flow rate. As the flow rate varies from design conditions, the mixing and residence times in the incinerator will vary and decrease the destruction efficiency. Design efficiency typically is 98% or higher.

5.5.3 Catalytic Oxidation

Catalytic oxidation, also called catalytic incineration, is similar in design and operation to thermal incineration except that a catalyst is present that enhances combustion. The catalyst is usually palladium or platinum in a metallic mesh, ceramic honeycomb, or catalyst-impregnated beads in a packed bed. The catalyst allows destruction to occur at lower temperatures than for thermal incineration (600-900°F). There is therefore less auxiliary fuel required and commensurate lower fuel costs.

Design efficiencies of 95 to 99% percent are typical. The catalyst can be damaged by overheating, so the air stream must be diluted, if necessary, to a VOC concentration below about 3000 ppmv, to maintain acceptable operating temperatures. Maintenance of this VOC level raises the capital and operating cost of the system since accurate monitoring of the gas stream

is needed, as is the ability to control the dilution of the gas stream. As for thermal incinerators, catalytic oxidation systems function best when the flow rate is constant.

The catalyst will become less effective over time and can be adversely affected by trace contaminants in the gas stream. Depending on the type of catalyst employed, it can be damaged by chlorinated hydrocarbons, mercury, phosphorus, or heavy metals.

5.5.4 Internal Combustion Engines (IC)

Industrial or automotive engines have been widely used to control VOC emissions from SVE systems. Depending on the engine size, air flows of 30 to 100 scfm have been treated. The effective flow rate is reduced, however, if ambient air must be added to the air stream to add sufficient oxygen to support combustion. As with other thermal treatment methods, supplemental fuel is needed.

Destruction efficiencies of 99+% have been reported for the most common components of gasoline (Pedersen and Curtis, 1991). Advantages of IC engines as controls are that the systems are portable, they can handle very concentrated air streams without the need for dilution, and the engine can provide power to operate the SVE system. Disadvantages are that the systems can only treat small flow rates and that manual supervision is required for a period during start-up to set the flow rates and operating conditions. Emissions of NO_x from the engine may be a concern in some locales.

5.5.5 Miscellaneous Control Approaches

A number of additional control devices may be applicable for controlling VOC emissions from SVE systems, including condensers, packed bed thermal processors, and biofilters. Condensers using chilled water or other refrigerants can remove anywhere from 50 to 90% of VOCs from concentrated streams (>5000 ppmv VOCs). Packed bed thermal processors consist of a bed of ceramic beads heated to 1800°F that is used to destroy organics and chlorinated hydrocarbons. Biofilters consist of soil beds that trap VOCs in a manner analogous to GAC and then are regenerated by biological action. Biotreatment requires time to establish an active culture of microbes and careful control of soil moisture, temperature, and air flow patterns to maintain the efficiency of the microbial action.

5.6 Costs For Remediation

The costs to install and operate an SVE system will vary from site to site. A typical cost to install and start up a small system is less than \$100,000 (Newton, 1990). Total capital costs for equipment range from \$65,000 to \$135,000, excluding the cost of each vapor-recovery well (Cochran, 1987). Typical capital costs for the major components of the system (Pedersen and Curtis, 1991) are \$2,000 to \$4,000 per well, \$10,000 or more for a vacuum pump (25 hp positive displacement blower), \$2,500 for an air/water separator, and \$10,000 for a structure to house the system. A major variable is the cost of any monitoring and control system needed to maintain the VOC level in the exhaust stream within preset limits. VOC control costs are discussed in the next subsection.

Typical operation and maintenance costs are \$6,000 to \$26,000 per year

(Cochran, 1987). The major operating costs (Pedersen and Curtis, 1991) are for power, VOC controls, monitoring, and labor. Power costs for a 10 hp system are estimated to be about \$600 per month. Monitoring and labor costs are highly variable. In general, operating costs in these areas can be minimized through the use of automated monitoring and control equipment. The optimal split for this trade-off between capital and operating costs will depend on the duration of the remediation and the proximity of the site to the labor source.

Remediation costs often are reported in terms of cost per volume of soil treated. Typical operating costs for SVE at a site with no off-gas treatment and no wastewater generated range from \$11 per ton at a large site with sandy soil to \$55 per ton at a small site with clay soil (Michaels, 1989b).

As discussed in Section 5.1, soil heating can enhance SVE performance. One option, hot air injection, is most cost-effective using electric immersion heaters for 50-kW or smaller systems. Natural gas burners are used for larger systems. The installed cost of a 50-kW hot air injection system, with stainless steel injection wells, is about \$15,000 to \$22,000; electricity cost is about \$3,600 per month. A 200-kW steam injection system burning natural gas will cost about \$35,000 to \$45,000 installed, with operating costs of gas and water of about \$7,500 per month (HWC, 1994a).

5.7 Costs For Emission Controls

Equations for predicting the costs of emission controls based on system design parameters are available (PES, 1989). Typical costs for various types and sizes of treatment systems are given in Table 5-2. The cost estimates are drawn from a number of vendors and, therefore, a range is shown

in most cases. The costs from different vendors may not be directly comparable since the cost basis may vary. For example, regenerable carbon adsorption systems cost from \$22,000 (one bed) to \$55,000 (six beds) for manually regenerated systems and about \$165,000 for a fully-automated equivalent system (Pedersen and Curtis, 1991). The cost data are intended to show the general level of costs likely to be incurred for various types of control options.

Maintenance costs will vary depending on the type of system and may include power, fuel, activated carbon, and the associated labor. The costs will vary with the size of the system and the operating rates. Electricity cost to run a 10-hp blower motor is about \$600 per month. Fuel costs for thermal incineration and catalytic oxidation depend on the VOC concentration of the influent air. Typical costs are \$500 to \$1,000 per month. Auxiliary fuel costs for IC engines are also about \$500 to \$1,000 per month. Activated carbon will cost from \$1 to \$2 per pound. However, an additional consideration is that an IC engine can power a generator, thus reducing electrical costs to operate pumps and blowers. Typical carbon costs are about \$25 per pound of hydrocarbons removed (about \$160 per gallon).

In terms of costs per volume of soil treated, one source estimates the cost of activated carbon can range from \$16 per ton to \$28 per ton (Michaels, 1989b). The cost of wastewater treatment or disposal (if required) is site-specific and may vary widely.

5.8 Equations and Models For Estimating VOC Emissions

The factors that govern vapor transport in the subsurface are very complex, and no theoretical models for predicting emissions or recovery rates for SVE systems exist that are considered accurate and reliable due to limitations in obtaining adequate input data. During operation of SVE systems, the vacuum that is applied to the soil and the resulting pressure gradient is the dominant factor in determining the flow rate of vapors. The induced vacuum in the soil decreases with distance from the extraction well, and a radius of influence exists that defines the extent to which vapors can be drawn to the well. The length of this radius depends on the strength of the vacuum source; the screened interval of the well; soil properties such as porosity, permeability, and moisture content; and site properties such as surface coverings.

In practice, field tests are typically performed to evaluate the potential effectiveness of SVE for a given site. The field tests may be either pilot-scale demonstrations of SVE or tests of the air permeability. This information is used to determine the number of wells required to remediate the site and the spacing of the wells.

Subsurface vapor flow equations based on Darcy's Law have been published that predict the flow rate of vented gas (Johnson, et al., 1990). The key inputs are the air permeability of the soil, the air-filled porosity of the soil, the thickness of the soil

Table 5-2
Summary of Capital Costs to Control VOC Emissions From SVE Systems

Treatment	Maximum Flow scmm (scfm)	Capital Cost (\$)
Carbon Adsorption (Regenerable)	3 (105)	20,000 ^a
	7 (250)	24,000 ^a
	14 (500)	33,000 ^a
	31 (1100)	12,000 ^b
Carbon Canisters	3 (100)	700
	14 (500)	8,000 ^c
	28 (1000)	6,000
	113 (4000)	23,000 ^c
Thermal Incineration	2 (70)	13,000 ^d
	3 (100)	25,000 ^d
	16 (570)	44,000 ^d
Catalytic Oxidation	3 (100)	25,000 ^e
	6 (200)	31,000 - 69,000 ^e
	14 (500)	44,000 - 86,000 ^e
	28 (1000)	77,000 ^f
	142 (5000)	140,000 ^g
Internal Combustion Engine	2 (60)	62,000
	3 (100)	50,000

Source: Adapted from Pedersen and Curtis, 1991.

^a Includes blower, demister, controls, gauges, valves, and flow ammeter.

^b Includes blower, flexible connector, and damper.

^c Deep bed units.

^d Includes blower, sampling valves, and controls. Heat recovery systems are not included

^e Includes burner, blower, flame arrestor, gauges, filters, knockout pot, sampling port, controls, and skid mounting.

^f Dilution system available for an additional \$22,000.

^g Source: Eklund, et al., 1992b.

layer, the density of the vapor, and the gradients of pressure and vapor concentration. Methods for measuring the air permeability are based on measuring the difference between the ambient atmospheric pressure and the air pressure in the soil during vapor transport.

Johnson, et al., (see Appendix E) describe a test where air is withdrawn from a well at a constant flow rate while the draw-down (vacuum) pressure is measured in a monitoring well some distance away. The pressure is plotted versus the log of time, and the slope of this equation is the air permeability. Measurements at several monitoring well locations are needed. Similar test methods may also be employed such as air injection tests and oil field tests including pressure buildup and draw-down tests (Pedersen and Curtis, 1991).

Various computer models are available for evaluating the feasibility, design, and performance of SVE systems. The U.S. EPA recently has evaluated some of the more commonly used models (Jordan, Mercer, and Cohen, 1995). The available models are described in Table 5-3.

For rough estimates of air emissions from SVE systems, data from pilot-scale tests at the site can be used with the following mass balance equation (Eklund and Albert, 1993):

$$ER = (C_g) \left(\frac{Q}{60} \right) (10^{-6})$$

where:

ER= Emission rate (g/sec);

C_g = Conc. in extracted vapors ($\mu\text{g}/\text{m}^3$);

Q= Vapor extraction rate (m^3/min);

$1/60$ = Conversion factor (min/sec); and

10^{-6} = Conversion factor ($\text{g}/\mu\text{g}$).

The extraction rate, Q, can be estimated from the results of pilot-scale tests at the site if any changes in pump size and number of wells between the pilot- and full-scale systems are taken into account. If no pilot-scale data are available, results of field tests of soil-air permeability can be used to estimate Q. If these too are not available, a default value can be used for the extraction rate. Typical flow rates for Q at Superfund sites range from $14 \text{ m}^3/\text{min}$ (500 cfm) to $425 \text{ m}^3/\text{min}$ (15,000 cfm), with a typical default value being $Q = 85 \text{ m}^3/\text{min}$ (3,000 cfm).

The contaminant concentration in the extracted vapors, C_g , can also be estimated from the results of pilot-scale tests at the site. The next best approach is to estimate C_g by collecting samples of the headspace vapors above the contaminated soil and measuring the concentration of the compound(s) of interest. These equilibrium soil-gas samples can be collected using ground (soil-gas) probes or by transferring soil samples from split-spoon samplers (to minimize VOC losses) to sealed containers and allowing the headspace to equilibrate.

Field data are required to get an accurate value for C_g . If no field data are available, however, a very conservative value for C_g can be estimated by assuming that the soil-gas is saturated. The maximum vapor concentration of any compound in the extracted vapors is its equilibrium or "saturated" vapor concentration, which is calculated from the compound's molecular weight, vapor pressure at the soil temperature, and the ideal gas law:

Table 5-3
Summary of SVE Models Evaluated by the U.S. EPA

Model	Type	Capabilities	Advantages	Limitations	Hardware/Software Requirements	Availability
Hyper-Ventilate, v2.0 (IBM PC) v1.01 (Apple MacIntosh)	Screening	Calculates air permeability, well flow rates, mass removal rate, mass removal from several idealized diffusion-limited scenarios Calculates contaminant concentrations over time for multiple constituents	Provides rapid estimates for determination of the potential feasibility of SVE Provides rapid estimates of contaminant concentrations in extracted gas, allows comparison of removal rates of different constituents	Analytical air flow solution Should not be used to design SVE systems	IBM PC or Compatible: 80386/80387 coprocessor or 80486, 4 MB RAM, DOS 3.1 or higher, Microsoft Windows 3.x and runtime version of Object PLUS Apple MacIntosh (Plus, SE, SE/30, II, IIX, or portable): 1 MB RAM, Apple HyperCard Software (v2.0 or greater)	Available from EPA as EPA/600/R-93/028 (EPA ORD Publications, 513-569-7562) ¹ Object PLUS available from Object PLUS Corp., 125 Cambridge Park Dr. Cambridge, MA 02140 ²
VENTING, v3.01	Screening	Calculates contaminant concentrations over time for multiple constituents	Provides rapid estimates of contaminant concentrations in extracted gas, allows comparison of removal rates of different constituents	User supplies flow rate to extraction well Simplistic one-dimensional representation of mass transport Should not be used to design SVE systems	IBM PC/AT or Compatible, DOS, 512 KB RAM, math coprocessor	Environmental Systems & Technologies, Inc. 2608 Sheffield Drive, Blacksburg, VA 24060-8270 703-552-0685

¹From NTIS: Report with disk (PB93-502664/AS)
Report only (PB93-134880/AS)

²From NTIS: IBM PC Disk (S/N 055-000-00427-7)
MacIntosh Disk (S/N 055-000-00403-0)

**Table 5-3
(Continued)**

Model	Type	Capabilities	Advantages	Limitations	Hardware/Software Requirements	Availability
AIRFLOW ^{EM} v2.07	Air flow	Calculates pressure distribution in a radial domain, calculates air flow pathlines and velocities	Easy-to-use 'CAD-type' graphical user interface which simplifies model input and setup Rapid setup aids in hypothesis testing for simple problems Many sample problems included with the code	Only allows for one extraction well No mass transport	IBM PC or compatible, 80386/80486, 4 MB RAM, DOS 2.0 or higher, mouse and math coprocessor for 80386-based machines recommended	Waterloo Hydrogeologic Software 19 McCauley Drive (RR#2) Bolton, Ontario, Canada L7E SR8 905-880-2886
CSUGAS	Air flow	Calculates vacuum distribution in the subsurface in inches of water	Allows full, three-dimensional analysis of heterogeneous, multi-well air flow problems Text-based input/output is flexible and up to the user	Lack of easy-to-use input/output interface may intimidate beginners No steady-state solution option No mass transport	IBM PC AT/XT or compatible, 640 KB RAM, DOS 2.0 or higher	Dr. James W. Warner Department of Civil Engineering Colorado State University Fort Collins, CO 80523 303-491-5048

**Table 5-3
(Continued)**

Model	Type	Capabilities	Advantages	Limitations	Hardware/Software Requirements	Availability
AIR3D	Air flow	Calculates pressure distribution in the subsurface	<p>Easy-to-use 'CAD-type' graphical user interface which simplifies model setup and input</p> <p>Allows three-dimensional analysis of complex problems</p>	<p>Users need an awareness of the operation and limitations of the MODFLOW code</p> <p>No mass transport</p>	IBM PC or compatible, DOS 3.3 or higher, 4 MB RAM, VGA card and color monitor, mouse is highly recommended	<p>American Petroleum Inst. 1220 L Street Northwest Washington, DC 20005</p> <p>The original version of AIR3D (without the GUI) is available free of charge from: USGS Book and Open File Reports BLDG 810, Box 25425 Denver, CO 80225</p>
VENT2D/ VENT3D	Air flow and multi-component contaminant transport	Calculates pressure distribution in the subsurface, multi component contaminant constituent concentrations over time in the subsurface	<p>Only readily available compositional flow and transport code</p> <p>Source code is available</p> <p>Text-based input/output is flexible and up to the user</p>	Grid size limited to 25 x 25 cells (can be increased with a different version available from the author)	IBM PC or compatible, 80X86 with math coprocessor, DOS 3.0 or higher, 525 KB RAM	David A. Benson 524 Claremont Street Reno, NV 98502 702-322-2104

Source: Jordan and Mercer, 1995.

$$C_g = \frac{(P_{vap})(MW * 10^9)}{(R)(T)}$$

where:

- C_g = Estimate of contaminant vapor concentration ($\mu\text{g}/\text{m}^3$);
 P_{vap} = Pure component vapor pressure at the soil temperature (mm Hg);
 MW = Molecular weight of component (g/mole);
 R = Gas constant = 62.4 L-mm Hg/mole-°K;
 T = Absolute temperature of soil (°K); and
 10^9 = Conversion factor ($\mu\text{g-L}/\text{g-m}^3$).

Values of molecular weight, vapor pressure at 25°C, and saturated vapor concentration at 25°C are given in Eklund and Albert, 1993. It is important to note that the above equation gives the theoretical maximum value of C_g . It will overpredict C_g for any compound present in the soil at relatively low concentrations. It will also overpredict the long-term average value of C_g since the concentration of contaminants in the gas extracted using a SVE system will tend to drop over time. It can drop by more than 95% in the first two days of operation, though pulsed operation will allow the soil-gas concentration to be periodically re-established at levels near the initial concentration.

The above equation assumes that an infinite source of vapors exists and that the contaminants are present in the soil or ground water at relatively high concentrations (e.g., total hydrocarbons of 500 ppm in the soil). Therefore, the vapor-phase concentration for a given compound is assumed to be independent of the

concentration of that same compound in the soil/liquid matrix.

Removal rates can be 500-600 kg/day or higher, and control efficiencies (when applicable) range from 60-99%. As previously mentioned, only about half of the sites listed used any VOC control equipment.

5.9 Case Study

Process Description

Terra Vac Incorporated has developed a vacuum extraction system designed to remove volatile organic contaminants from the vadose zone. At the Groveland, Massachusetts Superfund site, the contaminated air stream was treated with two sets of activated carbon canisters (Michaels, 1989a and Michaels, 1989b). Due to weather conditions, liquid water was extracted as well, so a vapor-liquid separator was included to remove contaminated water to a holding tank. The process design is shown in Figure 5-3. Air inlet wells were not used at this site.

Because no biodegradation was taking place in this case, the compounds released to the atmosphere were the same as those found in the soil. By far the most predominant contaminant removed was trichloroethylene, although 1,1,1-trichloroethane, trans-1,2-dichloroethylene, and tetrachloroethylene were also extracted.

Emission Factors

Table 5-4 shows emissions factors for each of the four contaminants. The estimated total VOC peak emission factor is 18 g/hr. Based on the field data, the carbon adsorption control device had an efficiency

Figure 5-3. Process Flow Diagram for Terra Vac In Situ Vacuum Extraction System.

Table 5-4
Estimated Emissions for Terra Vac's In-Situ Vacuum Extraction System

Pollutant	Molecular Weight g/mol	Peak Uncontrolled Stack Emissions g/hr^a	Peak Controlled Stack Emissions g/hr^b
Trichloroethylene (TCE)	131.29	1,712	17.1
trans-1,2-Dichloroethylene (DCE)	96.94	99.4	0.99
1,1,1-Trichloroethane (TCA)	133.41	13.6	0.14
Tetrachloroethylene (PCE)	165.83	3.18	0.03
Totals		1,830	18.3

^a Uncontrolled emissions equal removal rate of each contaminant.

^b Based on estimated 99% overall control efficiency for two carbon adsorption canisters in series.

of better than the 99% assumed in these calculations. In addition to stack emissions from vapor treatment, there would be evaporative emissions from contaminated water stored on-site in a holding tank. These emissions would add an estimated 3 g/hr to the total emissions. The removal efficiency for the total mass of contaminants present at the site was not demonstrated, nor was the associated control efficiency.

Costs

The equipment fabrication and construction costs were estimated to be \$55,000 (in 1991 dollars). The total cost to treat 6,000 tons of contaminated soil (removing 1,300 pounds of VOCs) at the site was estimated to be \$310,000 or \$52 per ton. Of this, costs for activated carbon were \$14 per ton and for liquid waste disposal were \$8 per ton. Including power and labor costs, the VOC control system represents about one-half of the total remediation cost.

5.10 References

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