- Contaminant concentrations in extracted soil gas, and how the concentrations initially vary with time
- Initial rate of contaminant mass removal (for sizing off-gas treatment units)
- Identification of constituents that may affect vapor treatment, e.g., tetramethyl lead or chlorinated solvents may be present that can potentially cause poisoning or deactivation of a catalyst
- Amount of vacuum that is necessary to induce a reasonable volumetric flow rate of air from each well
- Air permeability of the soil at each contaminated stratum
- ROI of each well

The 1991 EPA publications "Soil Vapor Extraction Technology" (EPA/540/2-91/003) and "Guide for Conducting Treatability Studies Under CERCLA: Soil Vapor Extraction" (EPA 540/2-91/019A) give detailed information on soil venting testing. The best preliminary test is a field pilot test, usually done with an ICE or a centrifugal vacuum blower rated at approximately 50 ft^3/min following a pair of drums containing activated carbon for emission control.

Details of laboratory column tests and field pilot tests are given in Section 8.5. A primary objective of field tests is to determine the ROI for extraction wells screened at each stratum. Then the well pattern can be designed to fit the aerial extent of the contaminant distribution that has been determined during site investigations. Test results give information for ft^3/min to vacuum and for calculating soil air permeability. Contaminant concentration measurements are needed to estimate the initial mass extraction rate and the emission abatement system operating requirements.

8.4.2 Radius of Influence of Extraction Wells and Soil Air Permeability

The ROI is that distance from an extraction point at which the observed vacuum reading is not significant. Setting a significant vacuum level is arbitrary, although sometimes it is related to the sensitivity of the vacuum gauges selected for the pilot test. Any amount of vacuum increase noted at an observation well or probe when the blower is on indicates that soil vapor is flowing from the observation point toward the extraction well. Sometimes vacuum levels in the range of 0.05 to 0.10 in. w.c. are selected to indicate the limit of the ROI. (This practice is disputed by Bohn (1997), who contends that the ROI is where the amount of induced vacuum is zero.)

In practice, it is usually found that the selected vacuum level is not exactly observed at the remote wells and probes. A curve is plotted showing the logarithm of observed vacuum readings versus radial distance from the extraction well at a given air flow rate, and extrapolated to an arbitrarily selected small vacuum. Or a linear regression of the absolute pressure (P) values equivalent to observed vacuum readings at each distance r from the extraction well can be fitted to Equation 8-11.

$$P^2 = a + b\,(\log r) \qquad (8\text{-}11)$$

in which r is the distance from the extraction well to the observation point, and a and b are empirical constants determined from the linear regression. From this equation (or from a plot thereof), the distance r that corresponds to the selected vacuum equivalent to P is the ROI. If all the data points fit well with this equation, the extraction well is probably extracting air from a homogeneous stratum.

Another method of arriving at the ROI is to plot observed vacuum versus distance from the extraction well at a given flow rate, and to select that distance to be the point just before the curve starts flattening out.

It should be noted that after the vacuum blower is started, it takes some time for vacuum readings and soil gas concentrations to become steady, at which time readings should be noted for use in the calculations.

The relationship among quantity of air flow through the soil, radial distance to the observation point, extraction vacuum, and observed vacuum depends on the extraction well screen length, air temperature, molecular weight and viscosity, well radius, and the air permeability of the stratum. The air permeability for successful soil venting should be at least 10^{-8} cm^2. Air permabilty can be calculated from Equation 8-12, adapted from Johnson et al. (1990).

$$K = [Q\ \mu\ \ln(r/R_w)]/[\pi b P_w\ (P_{atm}/P^{w})^2-1] \qquad (8\text{-}12)$$

in which k is the soil air permeability, cm^2; Q is the air flow rate, cm^3/sec; μ is the viscosity of air, 1.8×10^{-4} g/(cm-sec); b is the well screen length or sand-pack length, cm; P_w is the absolute pressure at the extraction well, g/(cm-sec^2); P_{atm} is 1 atm pressure, or 1.01×10^6 g/(cm-sec^2); r is the distance from extraction well to observation point, cm; and R_w is the radius of the extraction well bore hole, cm.

Examination of this equation indicates that for a given permeability value, k, the larger the radius of an extraction well bore hole, R_w, the higher is the air flow rate. This radius can be somewhat effectively increased by enlarging the sand packing around the well (Gomez-Lahoz et al., 1991).

The method of Johnson et al. (1990) for designing extraction well systems has been programmed for computer application; it is distributed by the EPA under the name HyperVentilate. The Macintosh computer version costs $17; the PC version costs $22. Both are available from the Superintendent of Documents, Box 371954, Pittsburgh, PA 15250-7954 (phone 202-783-3238). The Macintosh document order number is S/N 055-000-00403-0. The program includes these steps:

- The user may enter the relative amounts of each contaminant compound to be extracted from the soil or enter "fresh gasoline" or "weathered gasoline."
- The user enters the soil texture (i.e., medium sand, fine sand, silty sand, clayey silts) or the soil permeability.
- The user enters the well radius, ROI, length of the screened interval in the wells, and inches of water column vacuum. For the ROI, Johnson et al. (1990) suggest

40 ft (12 m) as a default value if the actual value is not known. Johnson et al. give Equation 8-13, which relates observed test pressure readings and ROI.

$$P = P_w \{1 + [1-(P_{atm}/P_w)^2] \ln(r/R_w)/\ln(R^w/R_I)\}^{1/2} \qquad (8\text{-}13)$$

in which, using consistent units, P is the remotely observed absolute pressure at distance r from the extraction well; P_w is the absolute pressure applied at the extraction well; R_w is the radius of extraction well bore hole; and R_I is the ROI.

- The program calculates the air flow rate range per well.
- The user enters the soil temperature, and the program calculates the contaminant extraction rates (in lb/day or kg/day) at the chosen amount of vacuum and at lesser amounts of vacuum.
- The user enters the estimated total mass of contaminant to be removed and the desired number of days of remediation, and the program calculates the maximum extraction rate range. (Note that the program assumes ideal circumstances, and the actual extraction rate over a period of time will be less than the predicted rate.)
- For each group of compounds within certain boiling point ranges, the program calculates the corresponding vapor concentrations and the residual concentrations in the soil.
- The program calculates the minimum amount of air that must be drawn through the soil per gram of initial contaminant to achieve at least a 90% reduction. The program calculates the number of wells needed and expresses this result as a range.

The program manual notes that calculated values are predictions that are intended to serve as guidelines. The program helps determine whether soil venting is an appropriate technology to apply at the described site.

The computer program Bioventing Plus^{TM}, marketed by Environmental Systems & Technologies (Blacksburg, Virginia) uses equations based on Johnson et al. (1990) and estimates hydrocarbon recovery rate versus time for multiwell systems. It also calculates the air permeability from field measurements of vacuum and air flow rate. Other models of soil venting have been developed by Wilson (Eckenfelder Inc., Nashville, Tennessee).

Figure 8-3, adapted from Appendix E of the US EPA (1991d), gives an order-of-magnitude relationship between soil air permeability and type of soil. The permeability scale units are Darcy's; multiply by 9.87×10^{-9} (approximately 1×10^{-8}) for equivalent permeability k in units of cm^2.

Other methods of estimating the soil air permeability are described as follows:

- Based on a correlation published by the U.S. Department of Commerce (1991), k is $125(D_{15})^2 \times 10^{-5}$ cm^2, in which D_{15} is the 15% particle size diameter in centimeters, passing by weight, as determined from a sieve analysis of the soil.
- Ratio the air permeability to hydraulic conductivity of the soil when saturated. If k is in cm^2 and hydraulic conductivity, K, is in cm/sec, k/K (which decreases with

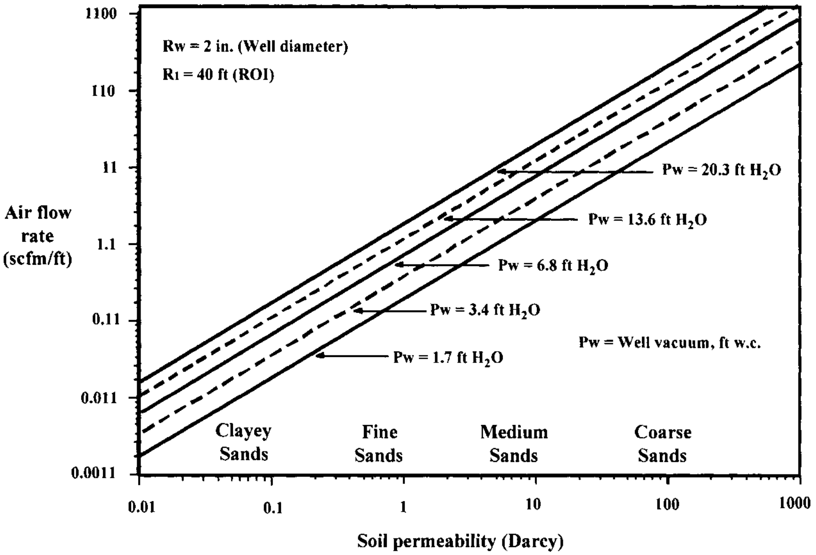

Figure 8-3 Air flowrate versus soil air permeability and applied vacuum (US EPA, 1991d, Appendix E).

temperature) has been estimated to be of the order of 10^{-3} at 50° F from data in the US EPA (1991c), or of the order of 10^{-5} from correlations in the US Department of Commerce (1991).

- Johnson et al. (1990) give Equation 8-14.

$$k = Q\mu/(4A\pi m) \qquad (8\text{-}14)$$

in which Q is the volumetric vapor flow rate from an extraction well, cm^3/sec; μ is the viscosity of air, 1.8×10^{-4} g/(cm-sec); m is the stratum thickness, cm; and A is the slope of the straight-line curve developed by plotting the pressure noted during testing at an observation well or probe versus the natural log of time. (Note that these pressure readings should be taken frequently during the first minutes when vacuum is applied.) The slope A can alternatively be used in Equation 8-15 from Johnson et al. (1990).

$$k = 10^{-8} r^2 e\mu/(4\ P_{atm})\ \exp(B/A + 0.5772) \qquad (8\text{-}15)$$

in which k is the air permeability, cm^2; e is the air-filled soil porosity (void fraction); B is the y-intercept of the straight-line curve, g/(cm-sec); A is the slope, g/(cm-sec^2); r is the radial distance from extraction well, m; μ is the viscosity of air, 1.8×10^{-4} g/(cm-sec); and P is the ambient atmospheric pressure, 1 atm = 1.013×10^6 g/(cm-sec^2). Note that if the soil moisture content increases, the permeability decreases.

Johnson et al. (1990), reprinted by the US EPA (1991d), provide multiplying factors for predicting the volumetric air flow rate from Figure 8-3 for variations in extraction well radius R_w and in the ROI, R_I, as given in Table 8-2.

Table 8-2 Multiplying factor applied to air rate for extraction wells (US EPA, 1991d, Appendix E).

R_w (in)	R_I (ft)	Air Flow Rate Multiplier
2	25	1.09
2	75	0.90
3	40	1.08
4	40	1.15
4	25	1.27

Johnson et al. (1990) note that the predicted air flow rate is not sensitive to changes in estimated radius of influence. This is true for the smaller well radii, as indicated in this tabulation for the multipliers corresponding to the 2-in. and 4-in. radius well sizes. An example (adapted from Appendix E of the US EPA, 1991d) using a 4-in. radius in a medium sand with a 5-ft screened interval for wells placed approximately 42 ft apart (25-ft ROI, so the multiplier is 1.27) is given in Table 8-3.

Table 8-3 Example of air flow rates (US EPA, 1991d, Appendix E).

Vacuum = 3.4 ft w.c. (3 in. Hg column)	**Flow Rate at Indicated Permeabilty**	
scfm/ft, Figure 8-3	0.41 at 1 Darcy	4.1 at 10 Darcy
scfm with 5-ft screen	2.1 at 1 Darcy	20.5 at 10 Darcy
scfm/well, corrected	x 1.27 = 2.6 at 1 Darcy	26 at 10 Darcy
Vacuum = 13.6 ft w.c. (12 in. Hg column)	**Flow Rate at Indicated Permeabilty**	
scfm/ft, Figure 8-3	1.3 at 1 Darcy	13 at 10 Darcy
scfm with 5-ft screen	6.5 at 1 Darcy	65 at 10 Darcy
scfm/well, corrected	x 1.27 = 8.3 at 1 Darcy	83 at 10 Darcy

In this example, a four-well extraction system with 42-ft well spacing would cover an area greater than 3,500 ft^2 (2 x 42 ft x 42 ft) with overlapping circles (25-ft radius) of influence. A centrifugal blower capable of extracting air with a vacuum of 3 in. Hg (plus the capability to overcome pressure drops in piping and emission abatement equipment) at each well should have a rating of approximately 100 scfm (four wells at 26 scfm per well). This would be a suitable blower selection for a conceptual design. High vacuum applications, such as the 12 in. Hg in this tabulation, would apply to clayey soils better than to the sandy soil given for this example. Final design and blower selection should be based on test results that would give a narrower range of permeability values.

The ROI at a given permeability is somewhat proportional to vacuum at the extraction well and is best determined from field pilot tests. Johnson et al. (1990) determine an air flow range that will result in extracting 90% of the contaminant mass during a desired time period.

8.4.3 Volumetric Air Flow and Contaminant Mass Removal Rate

Bohn (1997) suggests a flow rate of 16 to 50 m^3/hr (10 to 30 ft^3/min) per well. After an initial extraction period, higher air flow rates do not increase contaminant mass removal rates (during the diffusion-controlled period). Excessive air rates waste energy, require oversized vacuum-inducing and vapor treatment equipment, and dry the soil.

The initial mass removal rate of contaminants, and the basis for emission abatement equipment design, is the product of air flow rate, contaminant concentration, and contaminant vapor density, as shown in Equation 8-16.

$$\text{Rate (lb/min)} = Q\ (\text{concentration, ppmv}/10^6)\ d \qquad (8\text{-}16)$$

in which Q is the air flow rate, scfm; and d is the contaminant vapor density, lb/scf.

Under soil venting conditions, the ideal gas law holds and the air flow rate in scfm is equal to the actual measured air flow in ft^3/min multiplied by (1 atm divided by the actual absolute pressure) times (the actual absolute temperature divided by the standard temperature). If vacuum is measured in inches of mercury, 1 atm = 29.92 in. Hg. The absolute pressure is derived from the vacuum reading at which the actual air flow rate is measured. If the standard temperature is chosen to be 520° R (60° F), the density (in units of lb/scf) of any vapor component at this standard temperature and 1 atm is its molecular weight divided by 379. The effective molecular weight of gasoline is usually in the 95 to 111 range, with the high end of the range corresponding to gasoline that has had time to weather. During this time, the lighter (lower molecular weight) compounds, such as butanes and isopentane, volatilize, and the effective molecular weight gradually increases. An example of a mass extraction rate calculation is as follows:

Given: The air velocity measured in a 2-in. diameter pipe (pipe cross-sectional area is 3.1 in^2, 0.02153 ft^2) is 40 ft/sec; the vacuum is measured at 3.8 in. Hg; the temperature is measured at 55° F; the benzene concentration is 4,000 ppmv (benzene's molecular weight is 78 lb/lb mole); the total petroleum hydrocarbon (TPH) concentration is 50,000 ppmv.

Assumptions: Gasoline has weathered somewhat; the effective molecular weight is 105 lb/lb mole; and the standard temperature is 520° R.

Find: Mass extraction rate for benzene and for TPH.

Step 1: Determine the measured air flow rate in acfm and corresponding scfm units using Equations 8-19 and 8-20.

Vacuum = 3.8 in. of Hg (absolute pressure = 29.92 in. - 3.8 in. = 26.1 in. Hg) (8-17)
Temperature = 55° F (absolute temperature = 460° R + 55° = 515° R) (8-18)
Actual ft^3/min = 40 ft/sec (60 sec/min) (0.02153 ft^2) = 51.7 acfm (8-19)
Standard ft^3/min = 51.7 acfm (29.92/26.1) (520/515) = 59.8 scfm (8-20)

Step 2: Determine the density of the two contaminants of concern in this example using Equations 8-21 and 8-22.

Benzene vapor density = 78/(379 lb/scf) = 0.206 lb/scf (8-21)

TPH (weathered gasoline in this example) vapor density, molecular weight of 105,
= 105/(379 lb/scf) = (0.277 lb/scf) (8-22)

Step 3: Calculate the mass rate, scfm (ppmv/10^6), and the density using Equations 8-23 and 8-24.

Benzene rate = 59.8 scfm (4,000/10^6) (0.206 lb/scf) = 0.049 lb/min (8-23)
TPH rate = 59.8 scfm (50,000/10^6) (0.277 lb/scf) = 0.83 lb/min (8-24)

Note that TPH includes benzene and that the rates are not additive.

At a given air flow rate, the contaminant mass removal rate will decay markedly after the easily removed volatiles in the interstices of the soil particles or that are loosely bound on soil particle surfaces have been stripped.

Soil gas contaminant concentration levels may be constant for a period of time when soil venting is initiated. After soil gas concentration levels begin to decline, the decay in mass removal rate can be predicted from Equation 8-25.

$$M(t) = (M_o - M_f)e^{-kt} + M_f \qquad (8\text{-}25)$$

in which M(t) is the mass removal rate at any time t; M_o is the mass removal rate at the start of the decline in concentration from a steady level; M_f is the mass removal rate at the end of remediation; t is the time after the start of the decline in concentration from a steady level; and k is the decay constant.

Because M_o is usually much larger than M_f, the M_f terms can be dropped from the equation. The value of k is chosen so that the area of integration under the curve M(t) (plotted against time) is equal to the total mass to be extracted after the concentration starts declining. Or k can be evaluated at a known time t from the measured value of M_o and of M(t), as given by Equation 8-26.

$$k = \log_e[M_o/M(t)]/t \qquad (8\text{-}26)$$

In many applications, the concentration sometimes falls so low that it is best to stop the extraction for a few weeks and let the concentration build up. The extraction system is operated intermittently for a given set of extraction wells. Thus, the average concentration while operating the vacuum-inducing device is maximized.

For a given target mass removal, this mode of operation uses the least amount of energy and optimizes the use of any emission abatement devices. Bohn (1997) notes that a high rebound in concentration indicates that air flow rates per well have been excessive.

8.4.4 Ventilation Wells

Some of the wells in a soil venting field may be used for ventilation instead of SVE. There are situations in which some wells are installed for the purpose of admitting air into the soil. Three scenarios in which this is advantageous are as follows:

- When the air flows without ventilation wells are inadequate to achieve cleanup in a reasonable time using reasonable operating conditions.
- When ventilation wells are placed on one side of the contaminated soil and extraction takes place on the other side — this arrangement helps ensure maximum use of the extracted air for the purpose of vaporizing contaminants.
- When ventilation wells are placed in a row perpendicular to a line between extraction wells and another source of contamination that is off the property being remediated.

This arrangement accomplishes the same goal as in the first scenario and also helps guard against cleaning up someone else's property or cross-contaminating the main property of concern with different contaminants.

8.5 Treatability Studies for Soil Venting

Field pilot tests are a must for most in situ soil venting projects. Laboratory experiments done by drawing air through a column of undisturbed soil obtained by a geologist as a core sample have some marginal utility. The laboratory tests can determine the initial organic vapor concentration in the soil gas under dynamic air flow conditions; the partitioning that might be achieved — (the ratio of organics that vaporize to organics that stay adsorbed on the soil particles); and the order of magnitude of the soil air permeability. Appendix B of the EPA treatability studies guidance (US EPA, 1991c) recommends an air flow rate of 0.5 to 1.0 L/min through a 2.5-in. diameter soil column. Plots are made of vapor concentrations versus time and versus number of pore volumes of air passed through the column. The pressures recorded are plotted as a straight line against the $\log_e$ of time, and the slope of the line can be used for estimating the soil air permeability, as discussed in Section 8.4.2.

Field pilot extraction tests are best for determining permeability, initial contaminant extraction rate, and well ROI. Some extraction wells in the contaminated vadose zone are needed for field pilot tests. Results of the testing are used to determine the best locations for additional extraction wells. If the site has shallow contamination and is not paved, heavy plastic sheeting could be spread on the ground surface, extending aerially beyond the boundaries of the contaminated area and weighted down at the edges. Field pilot tests are best conducted by extracting from one well at a time, while monitoring vacuum and vapor concentrations versus time. At the same time, vacuum readings are taken at surrounding wells or soil probes. Extraction wells should be screened within only one soil stratum at a time. If remediation of multiple strata is needed, then multiple extraction wells must be tested separately during the pilot test runs. Each extraction well is tested at three different air flow rates, say in the range of 16 to 50 m^3/hr (10 to 30 ft^3/min).

A simple setup for a field pilot test has been used with a regenerative centrifugal blower creating negative pressure in each extraction test well. The blower discharges soil vapor, which is usually more than 90% air, through two 55-gal vapor phase activated carbon drums in series. It is important to monitor the temperature of the air between the two drums. If the air temperature rises above approximately 135° F, adsorption in the second drum will be severely impaired. In fact, the cooler the air, the better the adsorption, as long as the relative humidity is less than 50%. Two factors tend to cause increased air temperatures: heat of compression in the blower raises the temperature, and heat of adsorption on carbon raises the temperature further.

Soil vapor can have very high flammable vapor concentrations. The higher the concentration, the more heating occurs within the carbon bed. High concentrations can be extremely dangerous, and levels greater than 50,000 ppmv have been observed during pilot tests. The LEL for many hydrocarbons is in the range of 11,000 to 14,000 ppmv range. The centrifugal blower should be constructed of nonsparking materials and should accommodate dilution air so that concentrations are below the LEL in the extraction system.

An improved soil venting field pilot setup would have the soil vapor is drawn through a water knockout vessel (mist separator) and carbon vessels ahead of the blower. If the vapor concentration is monitored between the carbon and the blower and if operations are discontinued when breakthrough is attained, so that the LEL is not exceeded, a steel positive displacement blower can be used. The vapor extraction wells are usually screened only in the vadose zone, which is appropriate unless multiphase extraction with a shallow water table is desired. In that event, a liquid-ring vacuum pump would be a suitable vacuum-inducing device. Another method of conducting field pilot tests (for vadose zone extraction only) is to use an ICE.

8.6 Cost Estimating for Soil Venting

The main capital costs for soil venting systems are for the blower, inlet mist separator and filter, vapor treatment system, controls, shop assembly, sound-proofing, and field installation (which typically might include a slab, fencing, soil vapor piping connections, and utilities). As an example, a complete shop-assembled, skid- or trailer-mounted unit with all the main components including a catalytic oxidizer and controls costs $50,000 to $70,000 for units rated at 200 to 600 ft^3/min. Some units can be leased.

Trailer-mounted ICE units are available for purchase or lease. Units rated at less than 100 ft^3/min cost, in 1995, approximately $40,000 or rent for $3,500/mo. Larger units range in cost up to $100,000 or $9,000/mo. Extra costs are entailed to adapt the units for use of natural gas as auxiliary fuel, computerized monitoring accessories, noise muffler, and air pollution control permits.

Two 1991 EPA guidance documents (EPA /540/2-91/003 and EPA/2-91/019A) give capital cost ranges for extraction wells and equipment and costs of preliminary testing. Table 8-4 summarizes the reported 1991 costs for wells and equipment (excluding emission abatement equipment).

Table 8-5 gives the reported capital costs and alternative rental costs as of 1989 for carbon adsorption and catalytic oxidization systems. In this table, the capital cost for the ORS Model 1282008 catalytic oxidizer includes additional option features. The term "NA" is used where there is no available cost information. Table 8-3 also gives electric power requirements for operations. Preliminary laboratory tests in 1991 cost \$30,000 to \$50,000; field pilot tests cost \$10,000 to \$50,000 for determining soil air permeability and more than \$100,000 for complete pilot tests.

The US EPA (1992d) gives estimated costs for operating vapor treatment equipment. Use of activated carbon costs approximately \$45/kg (\$130/gal) of gasoline removed. Fuel cost for catalytic oxidizers is given as approximately \$400/mo. for each 100 ft^3/min of air treated using propane fuel priced at \$1/gal.

Baker and Moore (2000) give a comparison of costs for soil venting, thermal desorption, land farming, and bioventing for projects ranging from 500 to 20,000 yd^3 of soil remediated.

For thermally enhanced in situ soil venting, DuTeaux (1996) tabulates case histories as follows:

- \$252/yd^3 to \$317/yd^3 using in situ steam and air stripping of soil via hollow-stem augers for removal of VOCs and semivolatile organic compounds.
- \$15/ton to \$30/ton using resistive heating and radio frequency heating combined for removing fire training and chemical production wastes.
- \$63/yd^3 using heated vapor reinjection with vapor phase carbon adsorption for removing PCE, TCE, chloroform, and methylene chloride.

An important parameter in any remediation cost analysis is the life cycle of the operations. The life cycle of soil venting systems cannot be predicted accurately. Changes in the groundwater table elevation and infiltration from rain water can affect concentrations. Except when dealing with water-soluble volatile organics, such as acetone, some soil moisture helps in the desirable desorption of contaminants into the vapor phase. Too much moisture can undesirably decrease soil air permeability, however. Optimum usage of blower energy is usually achieved by ceasing extraction from a particular group of wells for a few weeks at a time so that depleted concentrations are allowed to be restored naturally. Factors such as changing soil water content and on-off operations affect the overall length of time to remediate a given site.