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3.1 INTRODUCTION

Soil vapor extraction (SVE) is an accepted, recognized, and cost-effective technology for remediating soils contaminated with volatile and semivolatile organic compounds. This technology is known in the industry by various other names, such as soil venting and vacuum extraction. The process involves inducing airflow in the subsurface with an applied vacuum, and thus enhancing the in situ volatilization of contaminants. Depending on the depth of soil being remediated, extraction of air laden with contaminant vapors can be achieved with vertical extraction wells or horizontal extraction pipes.

The SVE process takes advantage of the volatility of the contaminants to allow mass transfer from adsorbed, dissolved, and free phases in the soil to the vapor phase, where it is removed under vacuum and treated above ground. In order for this process to be effective, the contaminants of concern must be volatile enough and have a low enough water solubility to be drawn into the soil gas for removal. These properties are usually expressed by the vapor pressure and the Henry's law constant of the compounds.

Bioventing is a process that uses a similar approach to soil vapor extraction in terms of system configuration, but has a different objective. The intent of bioventing is to induce airflow to provide oxygen to maximize the aerobic biodegradation of the compounds, in contrast to volatilization. This difference in approach renders less volatile compounds also to be treated by enhanced biodegradation.

A typical in situ soil vapor extraction system couples vapor extraction wells with blowers or vacuum pumps to remove contaminant vapors from zones permeable to airflow. The components of an in situ soil vapor extraction system are shown in Figure 3.1, and are usually readily available as off-the-shelf products. The choices available to treat the contaminants present in the effluent air are many, and will primarily depend on the type of contaminants and the mass loading rate.

Soil vapor extraction has many advantages that make this technology applicable to a broad spectrum of sites.

- SVE is an in situ technology that can be implemented with a minimum disturbance to site operations.
- SVE is very effective in removing the volatile contaminant mass present in the vadose zone.
- SVE has the potential for treating large volumes of soil at acceptable costs.
- The system can be mobilized and installed very quickly.
- SVE as a technology can be easily integrated with other technologies required for site cleanup.
3.2 GOVERNING PHENOMENA

The basic phenomena that govern the performance of soil vapor extraction technology are very simple and easily described. The mechanisms that influence the success of SVE can be grouped into the following categories:

- Airflow characteristics in the vadose zone
- Mass transfer considerations that influence and limit the partitioning of the contaminants into the vapor phase and eventually into the soil gas

3.2.1 Airflow Characteristics

The basic principle of induced airflow during SVE is very simple. Airflow is induced in the subsurface by a pressure gradient applied through vertical wells or horizontal trenches. The negative pressure inside the extraction well, generated by a vacuum blower, causes soil air to move toward the well. Typical airflow patterns induced during SVE operation are shown in Figure 3.2. In order to design an SVE system, the subsurface airflow pathways and extraction flow rates must be properly defined.

The airflow field developed is dependent on many factors: the level of applied vacuum, available screen interval in the vadose zone, porosity, air permeability and its spatial variation, depth to groundwater, presence or absence of leakage from the ground surface, and subsurface conduits.

3.2.1.1 Mathematical Evaluation of Airflow

Three basic equations are considered in the description of airflow: the mass balance equation of soil air, the flow equation due to pressure gradients, and the equation of state.1

The mass balance of soil air is expressed by the equation of continuity.

\[
\phi_a \frac{\partial \rho_a}{\partial t} = -\nabla \rho_a \cdot V
\]  

(3.1)

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where \( \phi_i \) = air-filled porosity in soil \\
\( \rho_a \) = the density of soil air \\
\( V \) = velocity vector of airflow.

The airflow velocity due to the pressure gradient can be expressed by Darcy’s law when the slip flow is negligible. In the case of airflow in sand and gravel, the slippage of air on the soil wall is negligible and Darcy’s law for the flow in porous media can be applied.

\[
V = \frac{K_a}{\mu_a} \nabla p \tag{3.2}
\]

where \( K_a \) = the air permeability tensor \\
\( \mu_a \) = viscosity of air.

The density of air is a function of pressure and temperature. The relationship among these parameters is expressed by the equation of state. One of these equations of state is the ideal gas flow, which is simple and applicable for soil air at low pressure. The ideal gas law can be used because the operating pressure of the conventional SVE is close to ambient or lower. The ideal gas law for soil air is

\[
\rho_a = \frac{p \cdot (MW)}{RT} \tag{3.3}
\]

where \( (MW) \) = molecular weight of soil air \\
\( R \) = ideal gas law constant \\
\( T \) = the absolute temperature.

By combining the above equations, a general soil airflow equation can be obtained.

\[
\phi_i = \frac{V}{\nabla p} = \frac{\rho_a \cdot (MW)}{RT}
\]
3.2.1.2 Soil Air Permeability

Air permeability describes how easily vapors flow through the soil pore space. Since the airflow and the air permeability are linearly dependent, a higher air permeability will result in a higher flow rate at the same vacuum. There are numerous methods that could be employed for the determination of air permeability. The methods are listed below.

- Correlation to soil’s physical properties
- Laboratory measurement
- Field barometric fluctuation test
- Air injection test
- Pressure buildup test
- Pressure drawdown test

Correlation to soil’s physical properties. Soil air permeability is estimated from soil characteristics such as grain size distribution or hydraulic conductivity by assuming a linear correlation. This is a quick estimation method and provides only an order of magnitude estimate. This relationship is expressed by the following equation:

\[
K_a = K_w \left( \frac{\rho_a \cdot \mu_w}{\rho_w \cdot \mu_a} \right) 
\]

where

- \( K_a \) = air permeability
- \( K_w \) = hydraulic conductivity
- \( \rho_a \) = density of air
- \( \rho_w \) = density of water
- \( \mu_a \) = viscosity of air
- \( \mu_w \) = viscosity of water.

Example calculation:

At 68°F, for air and water, \( \rho_a = 0.0012 \), \( \rho_w = 1 \), \( \mu_a = 10,000 \mu P \), and \( \mu_w = 183 \mu P \). Therefore,

\[
K_a = K_w \left( \frac{0.0012 \cdot 10,000}{1 \cdot 183} \right) 
\]

\[
= K_w \{0.0656\}
\]

If

\[
K_w = 20 \text{ ft/day}
\]

\[
K_a = 20 \times 0.0656 
\]

\[
= 1.31 \text{ ft/day}.
\]
Laboratory method. Undisturbed soil samples are placed in pressure vessel (permeameter) and saturated with water. Air is injected to force fluid out of the sample. Measured airflow rates and air pressure in the sample are substituted into Darcy’s law equation to estimate soil’s air permeability. However, this method alters bulk density and soil structure and does not reflect the spatial variability of soil conditions in the field. Hence, this is not a recommended method to estimate the soil air permeability.

Barometric fluctuation test. This method monitors the changes in barometric pressure using piezometers installed within the vadose zone. Soil gas permeability is estimated by calculations that equate air flux between adjoining subsurface layers. However, normal diurnal barometric pressure changes interfere with the test if vadose zone is deep and the soil is very permeable. This test measures only vertical soil air permeability and is not recommended.

Air injection test. This is a field test in which a known volume of air is injected into the soil over a given time period. Pressure differential is measured before and after air injection and soil air permeability is calculated from Darcy’s law equation. However, inaccurate (high) estimates result due to dispersion of soil particles when air is injected, and so this test is not recommended.

Pressure buildup test. This is a test developed in the petroleum industry in which the downhole pressure increase is monitored after a vapor extraction well is closed or shut in. This test was designed to test confined vapor deposits. Vapor pressures found in contaminated soil may not create significant pressure buildup when well is closed. This method is not recommended.

Pressure drawdown test. This method is the most accurate soil air permeability test and was developed in the petroleum industry. The method involves measuring drawdown or gauge pressure in a monitoring well at a given distance from a vapor extraction well, while air is extracted at a constant flow rate. Field measurements of gauge pressure are typically taken from at least three monitoring wells located at varying radial distances from the extraction well to compensate for lateral spatial variations. The test is conducted over a short time period—long enough to extract at least one to two pore volumes of air, yet short enough not to be hampered by variations in atmospheric pressure and soil moisture condensation.

After the tests have been completed, soil air permeability is estimated graphically using the field measurements. This involves plotting the vacuum measurements at the monitoring well vs. the natural logarithm of the time from the initiation of the test and then determining the slope of the best-fit regression line through the data. The equation that approximates expected pressure changes over time is

\[ P' = \frac{Q}{4\pi mnK} \left\{ -0.5772 - \ln \left( \frac{r^2 \epsilon \mu}{4KP_{atm}} \right) + \ln(t) \right\} \]  

(3.6)

where

- \( P' \) = vacuum measured at monitoring well
- \( Q \) = extracted flow rate
- \( m \) = stratum thickness
- \( K \) = soil air permeability
- \( \mu \) = viscosity of vapor
\[ r = \text{distance of monitoring well where vacuum was measured} \]
\[ \varepsilon = \text{vapor-filled void fraction (0.0–1.0)} \]
\[ P_{\text{atm}} = \text{atmospheric pressure} \]
\[ t = \text{time from start of test.} \]

All of these parameters are obtained from the field and site data, except for the viscosity of air.

The slope \((A)\) and \(y\) intercept \((B)\) of the regression line of the pressure (negative) vs. natural log of time are given by the following equations:

\[
A = \frac{Q\mu}{4\pi m K}, \quad (3.7)
\]
\[
B = \frac{Q\mu}{4\pi m K} \left[-0.5772 - \ln \left( \frac{r^2 \varepsilon \mu}{4KP_{\text{atm}}} \right) \right], \quad (3.8)
\]

These equations can be used in two ways. If the flow rate from the extraction well \((Q)\) and the thickness of the screened interval from which vapors are being extracted \((m)\) are known, the soil air permeability \((k)\) can be calculated by solving equation (3.7) as follows:

\[
k = \frac{Q\mu}{4\pi m A} \quad (3.9)
\]

However, if \(Q\) and \(m\) are unknown, equation (3.7) is substituted into equation (3.8) and solved for \(K\):

\[
k = \frac{r^2 \varepsilon \mu}{4P_{\text{atm}} \left[ \exp(B/A) + 0.5772 \right]} \quad (3.10)
\]

Air permeability of soil is also a function of the soil’s intrinsic permeability \((K_i)\) and liquid content. At contaminated sites, liquid(s) present in soil pores is a combination of soil moisture and nonaqueous phase liquids (NAPLs). Soil air permeability \((K_a)\) can be estimated by multiplying the intrinsic permeability by the relative permeability \((K_r)\).

\[
K_a = K_i \cdot K_r \quad (3.11)
\]

where \(K_r\) is a dimensionless ratio (0.0–1.0), describing the variation in air permeability as a function of air saturation.

The equation below is useful in estimating soil air permeability as a function of air saturation and liquid content.\(^4\) The relative permeability is given by

\[
K_r = \left(1 - S_r\right)^2 \left(1 - S_r^{(2+2\lambda k)}\right) \quad (3.12)
\]

where
\[
\begin{align*}
S &= \theta / \varepsilon \\
S_r &= (S - S_r)/(1 - S_r) \\
S &= \text{degree of saturation} \\
\theta &= \text{volumetric moisture content} \\
\varepsilon &= \text{porosity of void space} \\
S_r &= \text{residual saturation}
\end{align*}
\]
$S_e =$ effective saturation
$\lambda =$ pore size distribution parameter.

When developing an estimate of relative permeability for a given soil matrix and liquid content, values of $e$, $S_r$, $S_e$, and $\lambda$ can be obtained from the literature.

As noted earlier, there are factors other than soil air permeability that govern the airflow field during soil vapor extraction.

**Porosity.** Soils with higher porosities will allow a higher flow for the same induced vacuum. Porosity influences the intrinsic air permeability and is related to the particle size distribution of soil. Coarse textured soil will generally have higher porosities and thus higher permeabilities.

**Subsurface conduits.** The presence of subsurface features that are less restrictive to flow may result in preferential flow in directions different than expected based on site geologic conditions. Subsurface utility conduits (electric, telephone, sewer, and water) may be bedded in materials much more permeable than surrounding soils. Preferential flow paths will be formed if these conduits intersect the zone of vacuum influence.

The impact of screen interval and leakage from the surface will be discussed in later sections.

### 3.2.2 Contaminant Partitioning

Contaminant partitioning characteristics govern the performance and thus the eventual shutdown of the system at the end of a successful site cleanup. Organic contaminants can be present in the soil matrix in four basic ways (Figure 3.3):

- As an adsorbed film on soil particles and colloids
- As a residual immiscible liquid in the soil pore spaces (NAPL)
- As vapor in soil air present in the pore space
- As dissolved compounds in soil pore water, and groundwater
- In addition, as a floating product above the water table in the case of LNAPLs and as a pooled or sinking liquid in the case of DNAPLs.

When soil air remains undisturbed after contaminant spillage and infiltration, it becomes saturated by contaminant vapors volatilized from the liquid phase. This highly saturated vapor will be removed initially when soil vapor extraction is initiated. As this soil vapor is purged from soil pores, the concentration of contaminants in the extracted soil air begins to decrease as the process shifts away from equilibrium (Figure 3.4). At this stage, the interfacial mass transfer between the contaminant and flowing air controls the removal of contaminants from soil. Soil air, due to soil vapor extraction, moves much faster than the phase transfer taking place from the immiscible liquids, soil pore water, and the adsorbed film into the soil gas.

Optimization of the performance of a soil vapor extraction system, at a given site, requires a fundamental understanding of the mechanisms controlling contaminant removal from that particular soil matrix. Under actual field conditions, several mechanisms will occur simultaneously, and the contribution of each will shift along with the progress of remediation. Early in the treatment, direct volatilization from immiscible liquids and adsorbed film will dominate. Extraction of dissolved contaminants from the pore water and desorption from the mineral and organic fraction of the soil will take place only when the liquid mass of the contamination is gone. For a water-miscible volatile organic compound (VOC) such as acetone, extraction from the pore water will occur during the early phase of treatment.
3.2.2.1 Contaminant Properties

The physical and chemical properties of a spilled compound control, to a great extent, the partitioning and thus the distribution into the various phases described earlier (vapor, dissolved in pore water, adsorbed to soil particles, and NAPLs).

The distribution of a compound among the four phases can be described by several parameters (Figure 3.5). The degree to which a compound partitions into the vapor phase is described by that compound’s vapor pressure and Henry’s law constant. The soil adsorption coefficient, $k_d$, describes the tendency of a compound to become adsorbed to soil. The solubility describes the degree to which a compound will dissolve into water.

3.2.2.1.1 Vapor Pressure

Vapor pressure is the parameter that can be used to estimate a compound’s tendency to volatilize and partition into the gaseous phase. All solids and liquids possess a vapor pressure,
and this parameter can be conceptualized as the solubility of the compound in air at a given temperature. More precisely, the vapor pressure is defined as the pressure exerted by the vapor at equilibrium with the liquid phase (NAPL) of the compound at a given temperature. Vapor pressure is typically expressed in terms such as millimeter of mercury (mmHg). Appendix C provides a listing of vapor pressures of the common environmental contaminants. Chemicals with vapor pressures greater than 0.5 to 1.0 mmHg (e.g., benzene, TCE) are expected to volatilize to a significant degree when released in the subsurface and will respond favorably to SVE technology.

For mixtures of compounds such as gasoline, the composition of the mixture also has a bearing on the vapor pressure according to the following relationship:

\[
P_i = X_i A_i P_i^\infty
\]

(3.13)

where \( P_i \) = equilibrium partial pressure of component \( i \) in the organic mixture
\( X_i \) = mole fraction of component \( i \) in the organic mixture
\( A_i \) = activity coefficient of component \( i \) in the organic mixture as a correction factor for compensating nonideal behavior\(^6,7\)
\( P_i^\infty \) = vapor pressure of component \( i \) as a pure compound.

The above relationship, for example, states that the vapor pressure of benzene is related to the percentage (mole fraction) of benzene in gasoline.

Temperature also has a strong influence on the vapor pressure of a compound. It is stated that for most intermediate molecular weight organic compounds, vapor pressure increases three to four times for each 10°C increase in temperature.\(^6\) In general, vapor pressure may be approximated by

\[
P(T) = A \exp(-B/T)
\]

(3.14)
where \( T \) = temperature in degrees Kelvin
\( A, B \) = constants characteristic of the substance.

Based on the effects of temperature, expressed by the above equation, SVE effectiveness in the subsurface can be influenced by increase in temperature. However, seasonal fluctuations in soil temperature are dampened with depth of the vadose zone. Steam injection, soil heating, and radio-frequency heating are some techniques that may enhance the volatilization of the compounds. However, cost-effective application of these techniques requires much more research and development. In diffusion-limited conditions, increase in temperature may result in beneficial effects in increasing volatilization.

If the contamination present is not in the form of separate phase liquids (NAPLs), vapor pressure becomes a less accurate predictor of SVE effectiveness. Contaminant adsorption to soil, and solubility in soil moisture will determine the relative volatility.

### 3.2.2.1.2 Water Solubility

The solubility of a compound controls the degree to which the compound dissolves into pore water present in the vadose zone. Solubility also has an important impact on the partitioning fate and transport of the compound. Soluble compounds are likely to dissolve and move into the saturated zone due to infiltration. A fluctuating water table is another means of impacting contaminant concentration in the vadose zone and specifically in the capillary fringe.

Solubility of a compound can be defined as the maximum mass that can dissolve in pure water at a specific temperature (aqueous concentrations are usually stated in terms of weight per weight (ppm, ppb) or weight per volume (mg/l, \( \text{mg/l} \)). For organic mixtures, such as gasoline, solubility is additionally a function of the mole fraction of each individual compound in the mixture. Appendix C presents the pure water solubilities for common environmental contaminants.

\[
C_i = X_i A_i C_i^o
\]

where \( C_i \) = equilibrium concentration of compound \( i \) in the organic mixture
\( X_i \) = mole fraction of compound \( i \) in the organic mixture
\( A_i \) = activity coefficient of compound \( i \) in the organic mixture as a correction factor for compensating nonideal behavior
\( C_i^o \) = equilibrium solubility of compound \( i \) as a pure compound.

Under typical SVE scenario, vadose zone soils are relatively moist (10 to 14% by weight), and contaminants are generally dissolved in pore water. Solubility is also an important parameter for bioventing, since biodegradation of a compound is enhanced due to the increased availability for microbial uptake as a dissolved compound.

Cosolvation is another factor that should be taken into account when evaluating partitioning of contaminants in the subsurface. Cosolvation refers to a mobile phase consisting of multiple solvents that are miscible in one another. For example, the cosolvents can be pore water, benzene, toluene, and TCE present in NAPL form. The solubilization of one contaminant into another will impact the partitioning and, thus, the removal efficiency under SVE operation.

### 3.2.2.1.3 Henry’s Law Constant

The volatilization of a compound dissolved in water is governed by Henry’s law, which describes the relative tendency for a compound in solution to exist in the vapor phase. It is somewhat analogous to the vapor pressure, which describes the partitioning behavior between
a pure substance—instead of a compound in solution—and its vapor phase. The proportionality constant that relates concentration in solution to the partial pressure is known as Henry’s law constant ($K_H$) and may be reported as “dimensionless” or as atm·m$^3$/mol.

\[ K_H = \frac{C_v}{C_l} \]  

(3.16)

where $K_H = $ Henry’s law constant
$C_v = $ concentration in vapor phase at the water–vapor interface
$C_l = $ concentration in liquid at the water–vapor interface.

Henry’s law constant is highly temperature-dependent and increases with increasing temperature. It is stated that Henry’s law constant increases 1.6 times for an increase of 10°C in temperature.\(^7\)

Appendix C lists the Henry’s law constants for common environmental contaminants, and the relationship between vapor pressure, solubility and Henry’s law constant is graphically presented in Figure 3.6. Under moist soil conditions, efficiency of SVE will be dependent on the Henry’s law constant of the compound, similar to air stripping.\(^8\) For example, although acetone is very volatile, efficiency of removal by SVE is very low due to its high solubility. Acetone tends to biodegrade very well and will be removed readily under bioventing.

### 3.2.2.1.4 Soil Adsorption Coefficient

Adsorption, absorption, and sorption are three terms that refer to similar phenomena.\(^9\) Adsorption is defined as the accumulation occurring at an interface, absorption as the partitioning between two phases (e.g., accumulation from groundwater into soil organic carbon), and sorption as including both adsorption and absorption.\(^10,11\) Often the terms adsorption and sorption are used interchangeably, as will be the case in this book.

In general, adsorption phenomena can be classified as either sorbent- or solvent-induced.\(^10\) Sorbent-induced adsorption occurs when there is an attraction between the soil matrix (sorbent) and the contaminants (solute) and the contaminant accumulates at the surface due to the affinity of the surface for the contaminant (e.g., cation exchange at the mineral sites). Solvent-induced adsorption occurs when the contaminant is hydrophobic (nonpolar, water-disliking, and low solubility) and finds it energetically favorable to accumulate at an interface or partition into a nonpolar phase (e.g., partitioning onto the soil organic carbon) rather than remain in the water phase.

Adsorption of contaminants to soil particles is impacted by the two phenomena described above. The soil organic content and its mineral adsorptive surfaces are both capable of contaminant adsorption. Adsorption of contaminants at both these locations increases the immobility of the contaminant and decreases the relative volatility during SVE. Soil adsorption becomes particularly important (rate-limiting) under drier conditions. Soil moisture may decrease as airflows continuously, during SVE, due to the vapor pressure of water being 10 mmHg at typical soil temperatures. Figure 3.7 illustrates the difference in adsorption potential under wet and drier soil conditions.

Adsorption of a contaminant to soil and organic matter is described by the contaminant’s soil adsorption coefficient, $K_d$. The total organic carbon (TOC) content, $f_{oc}$, strongly influences the adsorption capacity of nonionic organic compounds onto the soil matrix. Due to the nonpolar nature of most organic contaminants, there is little correlation between clay content and contaminant adsorption. While the adsorption coefficient, $K_d$, of a chemical has been observed to vary significantly from soil to soil (due to varying $f_{oc}$), it was observed that normalization of the $K_d$ values by the respective $f_{oc}$ values resolved in a parameter, $k_{oc}$, that

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was much less variable (independent of the soil and a function only of the compound). Another way of expressing this relationship is defining $K_{oc}$ as a proportionality constant.

$$K_d = f_{oc} \cdot K_{oc}$$  \hspace{1cm} (3.17)$$

where $K_d$ = partitioning coefficient

$f_{oc}$ = percentage of fraction of organic carbon in soils

$K_{oc}$ = organic carbon partitioning coefficient.

Typical values of $f_{oc}$ for subsurface soils have been reported in the range of 1 to 8%,

while alluvial sandy materials have been reported in the range of 0.02 to 1.0%. For soils with lower organic carbon content ($f_{oc} < 0.1\%$), adsorption to mineral grains may be dominant.

Researchers have evaluated a number of parameters for estimating $K_{oc}$ values based on fundamental properties of the contaminant. One of the easiest way of obtaining $K_{oc}$ is from the octanol–water partitioning coefficient ($K_{ow}$) of the contaminant. The $K_{ow}$ of a contaminant describes the partitioning between water (a polar phase) and octanol (a nonpolar phase). The octanol–water partitioning is analogous to the partitioning in the soil matrix between the pore water and soil organic matter. There are many equations reported in the literature to describe the relationship between $K_{ow}$ and $K_{oc}$. An example is provided by the equation below:  

$$\log K_{oc} = 0.999 \log K_{ow} - 0.202$$ \hspace{1cm} (3.18)$$

Most organic contaminants are more easily adsorbed to the soil than they are desorbed. Therefore, it takes much more time and energy for the desorption than adsorption of a
contaminant in the soil matrix. This phenomenon, known as hysteresis, tends to reduce the mass removal efficiency during SVE, particularly during the tail end of system operation.

3.2.2.1.5 Biodegradability of Contaminant

One of the most creative uses of SVE technology is in manipulating subsurface oxygen levels to maximize in situ biodegradation of aerobically biodegradable compounds in comparison to volatilization. This modification to conventional SVE is known as bioventing or bioenhanced soil venting. Bioventing can reduce effluent vapor treatment costs and can also result in the remediation of semivolatile organic compounds that are not readily volatilized.

Although microorganism populations in the vadose zone are sharply reduced in number and species diversity with depth, significant microbial degradation of some compounds occurs throughout the vadose zone. In bioventing, the natural biodegradation processes are enhanced by optimizing the system.

Most of the petroleum organic compounds such as benzene, toluene, ethylbenzene, and xylenes are very easily biodegradable under aerobic conditions. Some of the halogenated compounds such as methylene chloride and chlorobenzene will also biodegrade under aerobic conditions. Most of the alcohols, ketones, and phenolic compounds will degrade under aerobic conditions (see Appendix D).

In contrast to the compounds discussed above, microbial degradation of volatile aliphatic chlorinated compounds, such as TCE and PCE, occurs primarily by reductive dehalogenation. Reductive dehalogenation of these compounds will take place only under reduced, anaerobic conditions. Hence, biodegradation of aerobically nonbiodegradable compounds during SVE is nonexistent or insignificant.

3.2.2.1.6 Weathering

The concept of weathering applies to SVE due to the effect SVE has on the composition of the organic contaminant mixture present in the subsurface. At a gasoline spill site, initially at system start-up, the compounds removed will be primarily the more volatile, lighter-end fractions. As SVE proceeds, the extracted vapor will likely have less of the lighter-end fractions and will be composed mostly of heavier compounds. This process is commonly described as weathering. Changes in organic contaminant mixture characteristics taking place due to natural volatilization, solubilization, and biodegradation of the readily mobile lighter compounds is also characterized as weathering. The degree of weathering will impact the overall effectiveness of SVE operation.

3.2.2.1.7 Other Contaminant Properties

There are several other contaminant properties that may influence the volatility and thus effectiveness of SVE operation. These properties are not as significant as the parameters described in the last few sections, and hence may be considered secondary in importance.

These properties are molecular weight, molecular structure, and polarity. Heavier and large molecules travel slowly to and from soil micropores and tend to adsorb very strongly to soil surfaces. During the tail end of SVE system operation, these properties may end up as the rate-limiting mass transfer properties. This may be a significant factor at petroleum spill sites and may influence the degree of mass removal and the residual mass left behind after a reasonable time of SVE operation.

3.2.2.1.8 Contaminant Partitioning Summary

When a volatile NAPL is present in the soil matrix, the bulk of the mass removed during SVE will be due to direct volatilization influenced by the vapor pressures of the contaminants.
This is analogous to a fan blowing past a pool of gasoline or TCE. It has been reported in
the literature that more than 95% of NAPL can be removed after removing several hundred
pore volumes of air.\textsuperscript{15} In the presence of NAPL, mass removal rates are often linearly related
to the airflow rates. When NAPL is not present in the subsurface, airflow requirements become
very different, and are often governed by nonequilibrium rate-limiting conditions.

Under moist soil conditions and when there is no NAPL present, contaminant partitioning
in the vadose zone can be described by the following equation:\textsuperscript{16}

$$C_T = P_b C_A + w C_L + a C_G$$

(3.19)

where

- $C_T$ = total quantity of contaminant per unit soil volume
- $C_A$ = adsorbed chemical concentration
- $C_L$ = dissolved chemical concentration
- $C_G$ = vapor concentration
- $P_b$ = soil bulk density
- $w$ = volumetric water content
- $a$ = volumetric air content.

The equilibrium relationship between vapor concentration and the associated pore water
concentration is given by Henry’s law:

$$C_G = K_H \cdot C_L$$

(3.20)

where

- $C_G$ = vapor concentration
- $K_H$ = Henry’s law constant
- $C_L$ = pore water concentration.

The relationship between equilibrium dissolved concentration and adsorbed concentra-
tion is given by

$$C_A = K_d \cdot C_L$$

(3.21)

where

- $C_A$ = adsorbed concentration
- $K_d$ = adsorption coefficient
- $C_L$ = dissolved concentration.

Again, $K_d = f_{oc} \cdot K_{oc}$.

### 3.2.2.2 Soil Properties

The soil environment, like the contaminant characteristics, has a significant impact on the
effectiveness of SVE. Soil properties such as porosity, air permeability, water content, organic
matter content, heterogeneity, and surface seals impact the movement of contaminant vapors.

#### 3.2.2.2.1 Soil Porosity

Vapor migration in the subsurface occurs principally through air-filled pore spaces.
Factors influencing vapor migration include the air-filled porosity (which is affected by the
water content) of a soil and the orientation of the soil pores. Decreasing soil porosity will
generally reduce the efficiency of SVE due to the decrease in diffusive mass transport from
3.2.2.2 Water Content

Soil water content has competing effects on the air permeability. The primary effect of pore water is to reduce the air-filled porosity of soil. Research information is available to indicate that SVE would be more successful at lower water contents, since a greater percentage of the pore space will be air-filled and thus the induced airflow will be greater for a given vacuum.15,17

The water content also has a significant effect on the success of SVE through its effect on adsorption characteristics of organic compounds. Decrease in soil moisture allows for more contaminant adsorption onto the soil matrix to play a more prominent role in mass transfer during SVE. If the soil adsorptive capacities are strong, the benefits of soil dewatering may be partially offset due to the increased binding of contaminants.

Soil moisture may decrease as air is circulated through soil during SVE, since water has a vapor pressure of 10 mmHg at typical soil temperatures. As illustrated in Figure 3.7, under low soil moisture conditions, contaminants will adsorb directly on soil surfaces where fewer water molecules are competing for adsorption sites. A description of contaminant adsorption as a function of moisture content is also presented in Figure 3.8.18 Adsorption was the highest during oven-dry conditions and decreased linearly with moisture content up to one mono layer. Water sufficient to form 1 to 5 mono layers exhibited complex behavior due to interactions between the contaminant and surface bound water. At moisture contents greater than five mono layers, there was a gradual increase in adsorption which was attributed to increase in contaminant resolution.

3.2.2.3 Soil Heterogeneity

Soil heterogeneity is caused by the structure, stratification, type, and size of soil particles that influence both contaminant migration and subsurface airflow pathways. An example of heterogeneous soil conditions is a coarse silty sand formation with interbedded clay lenses. Another example is coarse sand formation overlain by a silty sand formation, and the preferred extraction well configuration under this condition is shown in Figure 3.9.

Preferred flow path due to highly permeable macropores formed by fractures, cracks, root casts, or earthworms should also be taken into consideration. The presence of subsurface features, such as utility conduits, may also result in preferential flow pathways. Preferred flow pathways have major implications with regard to SVE effectiveness due to potential short-circuiting of induced airflow pathways. If short-circuiting occurs, contaminants adhering to soils through which limited airflow occurs may not be removed as rapidly as those present in zones through which a large volume of airflows. Removal of contaminants from soil particles in dead zones would therefore be more closely related to diffusion effects (Figure 3.10). Removal of contaminants from these dead zones may not be enhanced by increased vacuum or flow rates, but rather removal will be limited by diffusion from these zones to the more continuous flow paths.

3.2.2.4 Surface Seals and Air Inlet Wells

The airflow pathways will be influenced by the amount of airflow entering near the extraction well (where the pressure gradient is the greatest). An impermeable surface seal prevents air from entering near the injection well and forces air to be drawn from a greater distance and thus contact a greater volume of soil (Figure 3.11). Surface seals may also prevent infiltration of rainfall, and thus reduce the amount of water removed by the extraction well.
Depending on the characteristics of the site, different materials can be used as an impermeable seal. Existing paved surfaces, such as asphalt or concrete layers, or a rolled-out flexible membrane lining can be used as surface seals.

Injection or air inlet wells can also be located at numerous places at a SVE site depending on the needs. The function of air inlet wells is to control the subsurface airflow and overcome preferential pathways and dead zones (Figure 3.12). Air injection wells are passive and can be installed at the edge of a site, so as not to induce flow of contamination from an adjacent site. Typically, injection and inlet wells are similar in construction and can be interchanged during SVE operation.
3.2.2.2.5 Depth to Water Table

If the SVE well penetrates the water table, the water table within the well will rise by an amount equal to the applied vacuum. A 60 in. water column vacuum at the well head will therefore result in a water table rise of 5 ft (Figure 3.13). Hence, if the screen of the SVE well is less than 5 ft, the rise in the water table will block the passage of air into the SVE.

Figure 3.11 Effect of surface seal on vapor flow paths.

Figure 3.12 Use of air injection wells during SVE operation.

3.2.2.2.5 Depth to Water Table

If the SVE well penetrates the water table, the water table within the well will rise by an amount equal to the applied vacuum. A 60 in. water column vacuum at the well head will therefore result in a water table rise of 5 ft (Figure 3.13). Hence, if the screen of the SVE well is less than 5 ft, the rise in the water table will block the passage of air into the SVE.
well. Even if the screen length is more than 5 ft, the effective radius of influence will be reduced. This situation will be encountered more in conditions where the water table is shallow and the well is inappropriately designed. Installing the bottom of the SVE well screen above the water table will minimize the impact caused by water table uplift. Horizontal wells or pipes installed in trenches can be used in shallow water table conditions, thus expanding the available screen length for airflow and enabling operation of the system at reduced vacuum levels. Under this condition the water uplift will be minimized (Figure 3.14).

However, the fluctuation of the water table will create conditions of screen submergence during certain times of the year. The need to induce airflow at or near the capillary fringe will also require the bottom of the screen to be placed very close to the water table.

3.3 APPLICABILITY

There are many criteria that need to be evaluated before deciding the applicability of SVE at a given site. The applicability of this technology is greatly influenced by the information obtained from contaminant and site characterization activities (Figure 3.15). Contaminant characterization will include composition, type, age, concentration, phase, and distribution of contaminants in the subsurface. Site characterization will include geologic conditions, soil moisture content, manmade site conditions, topography, depth to water table, and horizontal and vertical extent of contamination.
3.3.1 Contaminant Applicability

SVE is applicable when the contaminants present in the subsurface are volatile. As a simplified guideline, a compound or mixture of compounds is a likely candidate for SVE application if it has both of these characteristics:

- vapor pressure of 1.0 mmHg or more at 20°C
- Henry’s law constant greater than 0.001 atm·m³/mol, or greater than 0.01 in the dimension less form of Henry’s law constant.

Examples of contaminants amenable to SVE are listed in Table 3.1.¹⁹

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Henry’s law constant (atm·m³/mol)</th>
<th>Vapor pressure (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>0.00548 (25°C)</td>
<td>76 (20°C)</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.00674 (25°C)</td>
<td>22 (20°C)</td>
</tr>
<tr>
<td>Trichloroethylene (TCE)</td>
<td>0.00999 (20°C)</td>
<td>57.8 (20°C)</td>
</tr>
<tr>
<td>Tetrachloroethylene (PCE)</td>
<td>0.00029</td>
<td>20 (26.3°C)</td>
</tr>
</tbody>
</table>

The impact of solubility is reflected by the Henry’s law constant since the additive effects of solubility and vapor pressure are nonlinear. As noted in previous sections, the phase distribution, concentrations, and contaminant type will determine the mass removal efficiencies and the time required for site cleanup.
Evaluation of bioventing should be accompanied by the comparison of biodegradation rates to volatilization of the contaminants. If the contaminants are biodegradable, emphasis should be focused on the required mass removal rates and the time of cleanup. Presence of excessive levels of CO₂ and depletion of O₂ in the soil gas is an indication of ongoing natural biodegradation of contaminants in the vadose zone.

In most cases, the contaminant distribution is superimposed upon the geologic cross section of the area to be treated for the evaluation of SVE applicability. Appropriate laboratory methods should be used to analyze the volatile organic compounds (VOCs) present in the soil matrix. In some instances, it becomes necessary to empirically measure the optimal system performance rather than predict from theoretical considerations. Field-scale pilot studies and bench-scale (laboratory) experiments are cost-effective means of achieving this objective. Field-scale pilot studies will be described in a later section. Laboratory experiments can be used to determine the mass removal rates and to optimize the required airflow, moisture content, and other control parameters.

Laboratory experiments can be conducted using soil columns. The effect of variations in flow rate and other parameters on microscopic scale mass transfer limitations can be studied this way. However, it must be recognized that laboratory experiments are conducted on disturbed soil samples that are inherently unrepresentative of actual field conditions. In addition, it must be remembered that the soil sample to be tested is only representative of a very localized area of a given site.

3.3.2 Site Characterization

SVE is typically more applicable in cases where the contaminated unsaturated zone is relatively permeable and homogeneous. Geologic parameters such as porosity, soil structure, and air permeability influence the extractability of induced airflow. Site surface topography can also influence the success of an SVE system. Ideally the site should be covered by an impermeable surface to minimize short-circuiting of airflow and infiltration. The presence of utility trenches (generally constructed with high permeability fill material) will also cause short-circuiting of airflow pathways.

Site characterization activities include

- geologic and hydrogeologic characterization
- contaminant distribution assessment (vertical and horizontal)
- soil gas surveys
- water table elevation and fluctuations
- barometric pressure changes
- presence of LNAPL on top of the water table or isolated globules (“ganglia”) in the soil matrix
- groundwater concentrations.

Comprehensive geologic assessment will be complete only when information is collected on distinct geologic strata, subsurface conduits, depth to the water table, and seasonal fluctuation of the water table. Additionally, the estimated values of the physical properties (such as permeability, moisture content, organic carbon fraction) of each of the geologic strata should be collected. It is always important to develop detailed geologic cross sections in as many directions as possible. Most geologic cross sections are developed through analysis of drilling logs and site information available on tanks, pipes, etc. An example of a subsurface cross section used to evaluate the applicability of SVE is shown in Figure 3.16.
3.4 SYSTEM DESIGN

SVE technology has been implemented in the past using various design approaches which vary from an intuitive empirical approach to using sophisticated design models. The primary goals of SVE system design is to achieve the following objectives:

- Specification of system components such as vacuum blower, extraction wells, effluent air treatment unit, air/water separator, pipes, manifolds, etc.,
- Selecting operating conditions such as extraction vacuum levels, airflow rates, contaminant vapor concentrations, etc.,
- Estimation of cleanup levels, remediation time frame, residual concentrations, etc.,
- Meeting the constraints imposed by cost limits and permit limits, etc.

Prior to initiation of system design, a thorough evaluation of applicability of SVE should be completed. However, due to uncertainties and inherent limitations associated with natural heterogeneities, site characterization data, and accurate prediction of contaminant partitioning, system design objectives have to be realistic and flexible. Hence SVE system design has to incorporate modification of operating conditions even after system start-up. The additional cost required to build in adequate flexibility is usually very small compared to the potential benefits in the long term.

SVE system design activities can be grouped into two basic categories: selecting system operating parameters and selecting system components.

1. System operating parameters
   - extraction airflow rate
   - extraction vacuum
   - radius of influence
   - contaminant concentrations

2. System components and equipment
   - number of extraction wells
   - well locations
   - well construction (depth, screened interval)
   - extraction blower
   - air water separator
   - equipment manifolding and piping
   - instrumentation and control (measurement devices such as flow meters, pressure gauges, and control valves, etc.)
   - vapor treatment unit

Figure 3.16 Typical cross section at a candidate site for SVE.
Table 3.2 presents the significance of some design criteria on SVE system performance.

### Table 3.2 SVE System Design Criteria

<table>
<thead>
<tr>
<th>Design criteria</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The necessary vacuum to induce adequate airflow and radius of influence</td>
<td>The required vacuum dictates the type and size of vacuum pumps or blowers to utilize.</td>
</tr>
<tr>
<td>2. Airflow rates to achieve adequate mass removal and closure within required time</td>
<td>Airflow requirements will dictate vacuum equipment and air emission control equipment sizing. Airflow requirements to be dictated by modeling, pilot testing, and closure levels.</td>
</tr>
<tr>
<td>3. Number of vent wells to achieve closure within required time</td>
<td>The number of wells will be dictated by need to maintain adequate airflow in the subsurface. The pilot test in conjunction with the computer simulation will determine the number of required wells.</td>
</tr>
<tr>
<td>4. Well screen positioning</td>
<td>Positioning of the well screens will be critical to successful design. Well screens will be placed within the water table to accommodate water table fluctuations and will be screened at various intervals to ensure adequate flow throughout the soil. Screening intervals will be particularly important in ensuring that flow is induced in the most contaminated zone.</td>
</tr>
<tr>
<td>5. Soil moisture content monitoring and manipulation</td>
<td>Soil moisture controls air permeability and equilibrium concentrations. Its proper manipulation may enhance system performance. High moisture in the extracted air stream requires separation before vapor treatment.</td>
</tr>
<tr>
<td>6. Passive well placement</td>
<td>Passive wells provide influent air and should be located to minimize “dead,” no-flow zones that may develop in multiple extraction point configurations.</td>
</tr>
<tr>
<td>7. Off-gas treatment technology</td>
<td>Pilot-test data, cost analysis, and operation and maintenance logistics will enable the appropriate selection of off-gas treatment technologies.</td>
</tr>
<tr>
<td>8. Operation and maintenance and remote monitoring</td>
<td>If the property is to be developed and the wells will not be accessible, remote system monitoring needs to be considered.</td>
</tr>
<tr>
<td>9. No-failure piping and well design</td>
<td>Underground piping layout may consist of duplicate sections in sensitive areas to ensure nonfailure. All underground piping should be vacuum- or pressure-tested prior to burial.</td>
</tr>
<tr>
<td>10. Closure SVE system management</td>
<td>Management strategies should be developed for the last months prior to closure. System pulsing, passive venting with natural wind-driven vacuum can be considered.</td>
</tr>
</tbody>
</table>

3.4.1 Pilot Testing

It is prudent to perform a field pilot test at all SVE sites to determine whether the site is a suitable candidate for soil venting. Since the data collected during a pilot test involves collecting site-specific engineering design parameters, it is logical to call this test a field design test. Field design test activities are focused upon the collection of data to determine soil air permeability, zone of vapor extraction (radius of influence), extracted soil gas concentrations and composition, and the required flow rates and vacuum levels. Regardless of the size of the final system and site conditions, the field design test system should consist of the following components, at a minimum (Figure 3.17):

- vapor extraction test well
- vacuum blower to induce airflow
- at least three vacuum monitoring points, preferably at varying radial distances from the extraction well
- vapor treatment system (if required); vapor phase carbon may be sufficient for the field design test
- calibrated flow meter(s) or pitot tube(s)
- calibrated vacuum gauges
- sampling ports in the process lines

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A field design test usually consists of extracting contaminated air from the extraction well, at various flow regimes, and measuring the response to the applied vacuum in at least three monitoring points. The vacuum in the monitoring points is measured by installing vacuum seals and gauges on the surrounding monitoring wells and taking readings from them at different intervals during the various flow regimes. The extraction airflow rate from the venting wells is periodically measured, using flow meters or pitot tubes, at different time intervals of the various flow regimes. Air samples are taken from the extracted air at critical times of the test to analyze for the concentration and composition of contaminants. At least three air samples should be collected during each flow regime: one right after initiation of air extraction, one right before ending air extraction (after removal of at least one to two pore volume), and one during the middle of the test.

The extraction well location for the field design test should be selected within the area to be treated by the full-scale system. If the geologic conditions across the contaminated zone vary significantly, the need for more than one field testing location should be evaluated. The screened interval of the extraction well should be placed within the contaminated zone. Since induced airflow below the screened interval is generally not significant, the screen should be placed accordingly to attain the desired air distribution within the contaminated zone. Caution should be exercised to avoid any short circuit pathways (such as utility trenches) to obtain the best quality data.

The configuration of the typical SVE vertical well is shown in Figure 3.18. Horizontal wells or trenches should be considered for shallow water table conditions. In practice, existing groundwater monitoring wells have been used for SVE field design tests as vapor extraction wells. This is usually done to achieve cost savings, and caution must be provided to ensure that the screened interval of the groundwater monitoring well will provide the required air distribution.

A field design test will require at least three vacuum monitoring points in a homogeneous setting. The number of required monitoring points and the depths of installation will increase if the site geology is heterogeneous (Figure 3.19). Often one tries to locate the test in an area where existing groundwater monitoring points can be utilized as the vacuum monitoring.
points. Again, caution should be exercised to avoid compromise on the quality of data collected. Vacuum monitoring points can also be installed very cheaply with small-diameter driven points with perforations at the bottom.

The capacity of the vacuum blower to be used for the field design test is usually picked based upon experience, geologic conditions, the expected flow rate, and the power supply needs. Availability of various types of vacuum pumps within specific flow and vacuum ranges is shown in Figures 3.20 and 3.21. Depending on the site geologic conditions, a high flow, low vacuum regime or a low flow, high vacuum regime may be required. Two vacuum blowers operated in series or parallel may be required for the field design test to attain the flow regime under certain site-specific conditions.

The assembly and connection of the vapor extraction test well, with the vacuum blower, flow meters, and pressure gauges are shown in Figure 3.17. Since most vacuum blowers are driven by fixed-speed motors, extraction flow rates are often controlled by installing flow control valves and an air inlet/dilution valve at the suction end of the vacuum blower. Partial opening of the air inlet valve provides the means to control the airflow rate from the extraction well and also the potential for overheating of the vacuum blower. It is very important to locate the flow meters and vacuum gauges before the air inlet valve for accurately measuring the flow characteristics of the extraction well (Figure 3.17).

During the field design test, two to three flow regimes can be achieved by manipulating the air inlet/dilution valve. Initially, the air inlet valve should be closed when the vacuum blower is activated. The vacuum distribution in the soil should be allowed to reach steady conditions. One can check whether the steady condition is reached by reading the changes in induced vacuum at the vacuum monitoring wells. Usually stabilization takes place within the first 15 to 30 min of pumping. Then the following parameters should be monitored:

Figure 3.18 Typical SVE well.
1. Vacuum at the extraction wellhead
2. Flow rate from the extraction well
3. Induced vacuum at the monitoring wells
4. Concentrations and composition of the extracted air samples

The next step is to repeat the above steps by opening the air inlet valve to get 20 to 25% decrease in vacuum at the extraction wellhead. Similarly, the inlet valve can be opened further to get a 40 to 50% decrease in vacuum at the wellhead.

As noted earlier, the screening of the applicability of SVE should be performed before and during the field design test. As a summary of the discussion in previous sections, Table 3.3 presents the variables that will impact the applicability, selection, and design of an SVE system.

3.4.2 Design Approaches

3.4.2.1 Empirical Approach

This is the most simplistic of all the design approaches and is based upon previous experience, a good understanding of the site conditions, site constraints, general guidelines, and intuition. The design is based on the basic geologic information and the selection of system components to meet the predicted operating conditions. Unfortunately, performance of the resulting system may not meet the remediation objectives.

In some cases the use of existing system or a skid-mounted system bought from a vendor could be made to match the design objectives. However, this approach also will be inefficient in meeting the remediation objectives. The initial cost savings may be offset by poor system performance and potential redesign of the whole system.
Figure 3.20  Operational ranges based on available turbine vacuum pump models.

Figure 3.21  Operational ranges based on available regenerative vacuum pump models.
3.4.2.2 Radius of Influence Approach

This approach is the most widely used approach in the industry today. The extraction flow rate, vacuum, number of wells and their locations are selected based on the information obtained from a field pilot test. The pilot test is conducted to obtain steady state vacuum vs. distance relationships for a given site.

The steady state vacuum levels measured at monitoring wells located at varying radial directions are plotted on a semi-log graph paper, as shown in Figure 3.22. Vacuum levels are measured in various radial directions to compensate for the possible geologic variations in the subsurface. A best-fit line is then drawn through the points, as shown in Figure 3.22. The radius of influence of the extraction well is then determined as the distance at which a sufficient level of vacuum will be present to induce airflow. This “cut-off” vacuum level has been variously defined as 0.1 in. H₂O, 1.0 in. H₂O, or 10% of the applied vacuum at the extraction well. This arbitrary cut-off vacuum level is an empirical value based on prior experience and geologic conditions. The tailing effect of vacuum with distance is shown in Figure 3.23.

Once the radius of influence has been determined, overlapping circles with this radius are drawn on a site map over the zone of contamination (Figure 3.24). The number of wells and the locations of wells to cover the contaminated zone can be obtained this way. It must be noted that the vacuum vs. distance relationship may vary across the site and that the radius of influence may not be constant for all the extraction wells.

In this approach, the required screen lengths are estimated according to the depth of contamination as shown in a geologic cross section. Once the number of wells and the screen interval in each well has been selected, the total extraction airflow rate can be estimated using the curves shown in Figure 3.25. Selection of the appropriate vacuum blower can be done by matching the required airflow rate and the vacuum levels to the appropriate operating curve of various off-the-shelf blowers.

In practice, some sites may exhibit low flow, high vacuum conditions (less permeable geology) and other sites may exhibit high flow, low vacuum conditions (more permeable geology). Depending on the conditions encountered, it may be cost-effective to operate two smaller-capacity blowers in series or parallel instead of a single large-capacity blower (Figure 3.26).
Figure 3.22  Vacuum vs. distance plot on a semi-log paper.

Figure 3.23  Tailing effect of vacuum away from an extraction well.

Figure 3.24  Determination of the required number of wells from the radius of influence.
Computer simulation modeling is utilized to better design soil vapor extraction systems. This allows the model user to vary operating parameters and observe a simulation of the result. The type of models available for SVE system design can be classified into airflow models and multiphase transport models.

Flow-type models, available in the public domain, such as HYPER VENTILATE and AIR 3D, simulate only airflow under varying operating conditions. Airflow models therefore allow for selection and optimization of well placement and well screening within the contaminated zone. This selection is based on a predetermined, minimal acceptable airflow.

Figure 3.25 Aireflow generation plot.

Figure 3.26 Use of blowers in series or parallel.

3.4.2.3 Modeling Approach

Computer simulation modeling is utilized to better design soil vapor extraction systems. This allows the model user to vary operating parameters and observe a simulation of the result. The type of models available for SVE system design can be classified into airflow models and multiphase transport models.

Flow-type models, available in the public domain, such as HYPER VENTILATE and AIR 3D, simulate only airflow under varying operating conditions. Airflow models therefore allow for selection and optimization of well placement and well screening within the contaminated zone. This selection is based on a predetermined, minimal acceptable airflow.
Multiphase transport modeling allows for simulating the SVE process over time based upon the selected well layout. The multiphase transport models are therefore often preceded by simple airflow models that locate extraction wells. The multiphase transport models simulate the subsurface perturbation caused by the SVE system to the contaminant partitioning and predict contaminant concentrations within the various media at different time frames.

### 3.4.2.4 Example of a Modeling Approach

The governing equations of groundwater flow provide a good approximation to gas flow in the vadose zone, particularly when used to represent pressure gradients encountered in most SVE systems. The following are groundwater equations used for airflow in the vadose zone:

**Theis Equation**

$$s = \frac{114.6 Q}{T} W(u)$$

**Jacob Equation**

$$s = \frac{246Q}{T} \log \left[ \frac{2.246T}{r^2 S} \right]$$

where:
- $s$ = drawdown in feet of air
- $T$ = gas transmissivity in ft$^2$/day ($= K_s b$)
- $Q$ = flow rate in cfm
- $t$ = extraction time in days
- $r$ = distance from center of well in feet
- $S$ = storage coefficient
- $W(u)$ = Theis well function of $u$
- $b$ = vadose zone thickness in feet

Theis equation is valid for all $r$, and Jacob equation is not valid for larger $r$ (away from the extraction well). The limitations of both these equations are due to the assumption that there is no leakage of air from the surface and that airflows only in the horizontal direction.

The extrapolated logarithmic radius of influence $R$ is given by the following equation, (since in the Jacob equation $s = 0$ at the limit of radius of influence):

$$R = \sqrt{\frac{2.246T}{S}}$$

(3.24)

The straight-line approximation of the pressure drawdown data gives an underestimation of the actual radius of influence. Hence, the approach used in the radius of influence approach described in the previous section provides a conservative value for the radius of influence (Figure 3.27).

Substituting $R$ into the flow equations, they become steady state equations as follows:

**Theis (steady state approximation)**

$$s = \frac{114.6 Q}{T} W(u)$$

**Thiem (steady state version of Jacob equation)**

$$s = 528Q \cdot \log \left( \frac{R}{r} \right)$$

(3.25)
Multiplying coefficients in equation (3.23) by 12\( \times r \) to compute \( s \) in inches of water and for \( r \times g = 0.0012 \):

Theis  Thiem

\[
\begin{align*}
\text{Theis} & \quad \text{Thiem} \\
\frac{s}{T} &= \frac{1.65Q}{W(u)} & \frac{s}{T} &= \frac{7.6Q}{\log\left(\frac{R}{r}\right)} \\
u &= \frac{r^2}{1.781R^2}
\end{align*}
\]

In real life, significant amount of air leaks into the subsurface and the solution for the leaky vadoze zone (Figure 3.28) is given by the Hantush leaky equation. The Hantush leaky equation provides that

\[
\begin{align*}
s &= \frac{229\cdot Q}{T} K_{0}\left(\frac{r}{B}\right), \text{ for } s \text{ in feet of air} \quad (3.26) \\
s &= \frac{3.3\cdot Q}{T} K_{\infty}\left(\frac{r}{B}\right), \text{ for } s \text{ in inches of water} \quad (3.27)
\end{align*}
\]

where \( K_{\infty} \) = a Bessel function

\( B \) = leakage factor (0.89 \( R \)).
The Hantush leaky equation provides a more realistic approximation of the pressure–drawdown relationship for large values of $r$. It is recommended to use the Thiem equation near the extraction well and the Hantush leaky equation away from the extraction well. The Hantush equation exhibits greater vacuum at greater distances. The reason for this is because the percentage of air that comes through leakage near the well is not significant. The Hantush leaky equation should be used at distances of $u > 0.05$ and at a radial distance of $r$ which is 0.3 times the radius of influence.

The data requirements for simulating gas flow for SVE design include the following: steady state distance–drawdown data from a field pilot test (i.e., extraction rates, measured vacuums, well configuration); site map (showing buildings, paved and unpaved areas, pilot test well and monitoring well locations); and subsurface conformation (including boring logs, geologic cross sections, water table map or average depth to groundwater, and the extent of contamination). A typical approach to simulating gas flow might consist of the following steps:

1. Analysis of field pilot-test data—including plotting distance–drawdown data and applying the Theis or Hantush methods to estimate transmissivity and leakage
2. Calibration—reproducing the pilot test and adjusting model parameters to match observed vacuums
3. Simulation—using the calibrated model to examine the influence of various extraction well configurations; to examine the influence of vents, flow obstructions, paved areas, etc.; and to perform sensitivity analysis on key parameters such as air permeability and vertical leakage.

An example calculation of the above theory is described below. The vapor extraction test layout and data obtained from the pilot test is shown in Figures 3.29 and 3.30. The distance–drawdown data plotted is shown in Figure 3.31 on a semi-log paper.

Using the Thiem or Jacob equation and based on the semi-log analysis, determine the slope of the best-fit straight line, and use the equation

$$ T = \frac{7.6}{\Delta s} Q $$

(3.28)
where \( T \) = gas transmissivity in \( \text{ft}^2 / \text{day} \)
\( Q \) = flow rate in cfm
\( \Delta s \) = change in vacuum over one log cycle in inches of water.

\[ \Delta s = 8.1 \text{ from the plot (Figure 3.31),} \]
\[ T = \frac{7.6 \times 120}{8.1} \text{ for the } Q \text{ of the test (120 cfm)} \]
\[ = 113 \text{ ft}^2 / \text{day}. \]

When the \( Q \) changes, the \( \Delta s \) will also change.
There is another more accurate and preferred method to do the same analysis which is known as the leaky log–log analysis using the Hantush leaky method. Using this procedure, a log–log plot of vacuum vs. distance from the extraction well is prepared. On a separate graph having the same scale as the data plot, a standard leaky type curve is prepared by plotting the Bessel function \( K_0 \) against its argument \( r/B \). To analyze the data, overlay the data plot on the type curve and, while keeping the coordinate axes of the two plots parallel, shift the data plot to align with the type curve, effecting a match position. Select and record the values of an arbitrary point referred to as the match point anywhere on the overlapping part of the plots (Figures 3.32 and 3.33). Record the match point coordinates: \( s, r, K_0, r/B \).

Figure 3.32 shows the leaky type curve by plotting the Bessel function \( K_0 \) against its argument \( r/B \). \( K_0 \) is the modified Bessel function of the second kind and of zero order. Tables of Values of this function are readily available.\(^{25} \)

Figure 3.33 shows the data from the pilot test plotted on a log–log graph having the same scale as that used for the type curve. Figure 3.34 shows the data and type curve superimposed, effecting a position of best fit.

Gas transmissivity is computed from the formula shown here using the match point values for \( s \) and \( K_0 \).

\[
T = \frac{3.3Q}{s} K_0
\]

where

- \( T \) = transmissivity in ft\(^2\)/day
- \( Q \) = flow rate in cfm
- \( K_0 \) = match point value from type curve graph
- \( s \) = match point value from distance–drawdown graph.

The leakage factor \( B \) is computed from the equation shown here using match point values \( r \) and \( r/B \).

\[
B = \frac{r}{r/B}
\]
where \( B \) = leakage factor in feet
\( r \) = match point value from distance–drawdown graph
\( r/B \) = match point value from type curve.

The log extrapolated radius of influence is computed from leakage factor.

\[
R = \frac{B}{0.89}
\]
The leakage is computed from the leakage factor and gas transmissivity. “Leakance”, $l$, is defined as the ratio $K' b'$ where $K'$ and $b'$ are the gas conductivity and thickness, respectively, of the resistive layer separating the vadose zone from the atmosphere. All of the vertical resistance of the vadose zone sediments is assumed to be concentrated in a thin “leaky” layer at ground surface.

$$l = T/B^2$$

From the above exercise the obtained match point values and computed vadose zone parameters are presented below:

$$K_o = 0.421$$

$$r/B = 1$$

$s = 1.51$ in.

$r = 52$ ft

$$T = \frac{3.3 \times 120 \times 0.421}{1.51}$$

$$= 110 \text{ ft}^2/\text{day}$$

$$B = \frac{52}{1} = 52 \text{ ft}$$

$$R = \frac{52}{0.89} = 58.4 \text{ ft}$$

$$l = \frac{T}{B^2} = \frac{110}{52}$$

$$= 0.041 \text{ day}^{-1}.$$
Because the Hantush equation is valid for all distances around the extraction well, the leaky analysis is preferred. The semi-log procedure can sometimes overestimate $T$ and $R$, since the Jacob and Thiem equations are only valid near the well. If the pilot test incorporates vacuum monitoring wells beyond the valid range of the Jacob and Thiem equations, erroneous values will result.

Figure 3.35 shows vacuums observed in wells located 5, 10, 20, and 40 ft from the vapor extraction well. Data for the two wells nearest the extraction well fall on the straight-line logarithmic plot, whereas data from the two distant wells do not. If semi-log analysis is performed using the two closest wells, valid values for transmissivity and log-extrapolated radius of influence will be obtained. If the distant wells are used, however, the straight line of best fit is flatter, and both $T$ and $R$ are overestimated (Figures 3.36, 3.37, 3.38). Using leaky analysis procedures, all observed vacuums fall on the leaky type curve, so the correct $T$ and $R$ values are obtained regardless of which vacuum monitoring wells are used.

Application of the equations can be clarified with some examples given in the following five problems.

Problem 1: Given

- fine sand formation with estimated $K_w$ of 3 ft/day
- water table at 40 ft
- extraction well has 12 in. bore hole (0.5 ft radius),

what flow rate $Q$ can be expected from a blower having a vacuum of 80 in. of water?

Estimate gas conductivity:

$$K_g = 0.0656 \cdot K_w$$

$$= 0.0656 \cdot 3$$

$$= 0.20 \text{ ft/day.}$$
Calculate gas transmissivity:

\[ T = K_s \cdot b \]
\[ = 0.20 \cdot 40 \]
\[ = 8.0 \text{ ft}^2/\text{day}. \]

In the absence of pilot test data, estimate radius of influence to be 40 ft.

Using Thiem equation to solve for \( Q \):

\[ Q = \frac{sT}{7.6 \log(R/r)} \]
\[ = \frac{80 \cdot 8.0}{7.6 \log(40/0.5)} \]
\[ = 44.3 \text{ cfm}. \]

**Problem 2:** If subsequent pilot test data show \( R = 27 \) ft (by extending the straight line to \( s = 0 \)), calculate the vacuum in an observation well 36 ft away from an extraction well producing 40 cfm.

Step 1 is to calculate the leakage factor from the radius of influence determined during the pilot test.

\[ B = 0.89 \cdot R \]
\[ = 0.89 \times 27 \]
\[ = 24 \text{ ft}. \]
Step 2 is to determine the ratio $r/B$

$$\frac{r}{B} = \frac{36}{24} = 1.5.$$  

Step 3 uses tables of Bessel function values to obtain the $K_o$ value corresponding to the previously computed ratio $r/B$ from tables:

$$K_o[r/B] = K_o(1.5) = 0.214.$$  

Step 4 employs the Hantush leaky equation to compute vacuum at a distance from the extraction well.

Figure 3.37 Vapor extraction test data analysis (near observation wells give correct $T$ and $R$ values).

Figure 3.38 Vapor extraction test data analysis (observation wells give wrong $T$ and $R$ values).
Problem 3: At 40 cfm of airflow rate, what is the maximum distance of effective remediation of this well?

The first step is to establish a reasonable criterion for determining whether or not remediation will be adequate. A common procedure is to require a minimum of 0.1 or 0.2 in. of vacuum as the cut-off value at the point of concern. Another criterion is to require a minimum air velocity. For this example, 0.1 in. of vacuum will be used.

For Step 1, establish criterion, e.g., \( s \) required = 0.1 in.

For Step 2, use the Hantush equation and the known parameters to compute the value of the Bessel function, \( K_o \). Find \( r \) for which \( s = 0.1 \) in. Solving the Hantush equation for \( K_o \):

\[
K_o[r/B] = \frac{sT}{3.3 \cdot Q}
\]

\[
= \frac{0.1 \cdot 80}{3.3 \cdot 40}
\]

\[
= 0.006.
\]

Step 3 uses tables of Bessel function values to obtain the corresponding \( r/B \) ratio from which \( r \) can be computed. From Bessel function tables, the \( K_o \) value closest to 0.006 is 0.00623, which corresponds to \( r/B = 2.5 \). Thus,

\[
r = 2.5 \cdot B
\]

\[
= 2.5 \cdot 24
\]

\[
= 60 \text{ ft}.
\]

The basic equations discussed earlier are valid only under the following assumptions:

- air is incompressible
- the well is 100% efficient
- the well is fully penetrating.

If any of these assumptions are violated, the standard equations must be corrected to compensate this for deviation from the assumptions.

Corrections For Gas Expansion. If the magnitude of vacuum exceeds 0.15 to 0.2 atm, the actual drawdown (vacuum) will deviate from the drawdown predicted by the equations, and a correction factor is required. Normally, vacuums this large are only observed at the extraction well itself and thus corrections are done only for the extraction well.

The equations shown here provide the correction factors needed to convert theoretical to actual vacuum and vice versa. At sea level, atmospheric pressure is 14.7 psi.
where \( s_t \) = theoretical drawdown (from equations) \\
\( s_a \) = actual drawdown observed in the field \\
\( P_{atm} \) = atmospheric pressure expressed in the same units as \( s_t \) and \( s_a \).

At sea level,

\[
P_{atm} = 14.7 \text{ psi, if } s \text{ is expressed in psi} \\
= 33.8 \text{ ft, if } s \text{ is expressed in ft} \\
= 406 \text{ in., if } s \text{ is expressed in inches.}
\]

**Problem 4:** From the previous problem, \( T = 8.0 \text{ ft}^2/\text{day} \) and \( B = 24 \text{ ft} \). What would the flow rate be with an applied vacuum of 12 psi? This problem requires correcting for gas expansion, since the vacuum exceeds 0.2 atm.

For Step 1, the standard correction equation is used to compute an equivalent theoretical vacuum.

\[
s_a = 12 \text{ psi} \\
s_t = s_a - \frac{s_a^2}{2P_{atm}}
\]

\[
= 12 - \frac{12^2}{2 \cdot 14.7} \\
= 7.1 \text{ psi.}
\]

Expressed in inches,

\[
s_t = 7.1 \cdot 2.3 \cdot 12 \\
= 196 \text{ in.}
\]

For step 2, the theoretical vacuum may be used in the Thiem equation to compute the anticipated airflow.

\[
Q = \frac{sT}{7.6 \log(R/r)}
\]

\[
= \frac{196 \cdot 8.0}{7.6 \cdot \log(27/0.5)} \\
= \frac{196 \cdot 8.0}{7.6 \cdot 1.732} \\
= 119 \text{ cfm.}
\]
The equations shown here have incorporated both the Thiem equation and the gas expansion correction into a single formula. The two equations are equivalent, one solving for vacuum, \( s \), and the other solving for discharge, \( Q \). When you find SVE airflow equations in the literature incorporating pressure squared as part of the formula, they are equivalent to the equations shown here. They are often written in terms of intrinsic permeability (\( K \)), gas density (\( \rho \)), and viscosity (\( \mu \)), which tends to make them more confusing. The simplest approach is to use the standard airflow equations adapted from groundwater equations and apply the gas expansion correction as a separate step.

\[
s = P_{\text{atm}} - \sqrt{P_{\text{atm}}^2 - \frac{15.2 \cdot P_{\text{atm}} \cdot Q \cdot \log(R/r)}{T}}, \tag{3.31}
\]

\[
Q = \frac{T}{7.6 \cdot \log(R/r)} \left( s - \frac{s^2}{2P_{\text{atm}}} \right). \tag{3.32}
\]

It should be noted that \( P_{\text{atm}} \) is expressed in inches of water.

SVE well inefficiency, \( E \), is demonstrated by a greater vacuum inside the borehole than outside (Figure 3.39). This difference in vacuum represents the head loss associated with drilling damage in the vicinity of the borehole. It is estimated by extending the drawdown curve left up to distance equal to borehole radius and comparing that value to the actual measured vacuum.

\[
E = \frac{s_{\text{outside}}}{s_{\text{inside}}}. \tag{3.33}
\]

![Figure 3.39 Illustration of well efficiency.](image-url)
The theoretical equations use \( s_{\text{outside}} \) not \( s_{\text{inside}} \). Inefficiency is caused by pressure losses across the well screen, reduced permeability of sediments around the borehole, and other local factors. For a 100% efficient well, the drawdown inside the borehole is the same as the drawdown outside, so no correction is required. For a 60% efficient well, the vacuum outside the borehole will be 60% of that inside. For a 30% efficient well, the vacuum outside the borehole will be 30% of that inside.

**Problem 5:** Recompute \( Q \) in Problem 1 based on a \( T \) of 8.0 ft\(^2\)/day, \( s \) of 80 in., the actual \( R \) of 27 ft (from the pilot test), and well efficiencies of 100%, 60%, and 30%.

For 100% efficiency, no correction is required.

\[
Q = \frac{sT}{7.6 \log(R/r)}
\]

\[
= \frac{80 \cdot 8.0}{7.6 \cdot \log(27/0.5)}
\]

\[
= 48.6 \text{ cfm.}
\]

(We got 44.3 cfm when we assumed \( R = 40 \) ft.) For 60% efficiency:

\[
s_{\text{outside}} = 0.6 \ s_{\text{inside}}
\]

\[
= 0.6 \cdot 80
\]

\[
= 48 \text{ in.}
\]

\[
Q = \frac{48 \cdot 80}{7.6 \log(27/0.5)}
\]

\[
= 29.2 \text{ cfm.}
\]

For 30% efficiency:

\[
s_{\text{outside}} = 24 \text{ in.}
\]

and \( Q = 14.6 \text{ cfm.} \)

**Correction for Partial Penetration.** In partially penetrating systems, converging flow complicates the flow and drawdown distribution, thus resulting in different drawdowns than predicted by the standard equations. Before using the standard equations, the drawdowns must be corrected for partial penetration in a manner exactly analogous to procedures used for groundwater pumping tests. Pilot test data must be corrected to equivalent, fully penetrating values prior to analysis. Likewise, calculated drawdowns for the final remediation system must be corrected back to partially penetrating values.

As in groundwater pumping tests, the Hantush partial penetration equation may be used to provide the required correction factors. The Kozeny equation may also be used, but only at the extraction well.

- If screens do not fully penetrate the vadose zone, flow converges (distorts), resulting in complicated drawdown distribution.
Pilot test data must be corrected for partial penetration prior to analysis.

Calculated drawdown values must be corrected for partial penetration to predict actual well performance.

Apply Kozeny correction factors to extraction well.

Apply Hantush correction factors to observation wells as well as extraction well.

3.5 BIOVENTING

In most cases, SVE has been primarily applied for the removal of volatile organic compounds from the vadose zone utilizing volatilization as the primary mass transfer mechanism. However, circulation of air in the vadose zone soils can be utilized to enhance the degradation of volatile organic compounds which are aerobically biodegradable (Figure 3.40). Bioventing can reduce vapor treatment costs and can also result in the remediation of semi-volatile organic compounds that cannot be removed by direct volatilization alone.\(^\text{15,25}\)

In bioventing, the aerobic biodegradation processes are optimized to become the dominant process by modifying the venting system. Bioventing systems use the same blowers used in SVE systems to provide specific distribution and flux of air through the contaminated vadose zone to stimulate the indigenous microorganisms to degrade the contaminants to more benign compounds such as carbon dioxide, water, and biomass. For example, degradation of benzene takes place according to the equation

\[
C_6H_6 + 7 \cdot 5 O_2 \rightarrow 6CO_2 + 6H_2O + \text{biomass}. \quad (3.34)
\]

Based on the above equation about 3.5 g of O\(_2\) are required per gram of benzene degraded. This method is relatively powerful, because atmospheric air contains 21% oxygen. During implementation of bioventing, soil gases present in the subsurface are generally monitored to ensure the presence of aerobic conditions. The gases monitored are O\(_2\), CO\(_2\), and CH\(_4\). Increased levels of CO\(_2\) (atmospheric level is 0.03%) and depletion of O\(_2\) indicates a higher level of microbial activity. However, at several sites,\(^\text{26}\) oxygen utilization has proven to be a more useful measure of biodegradation rates than carbon dioxide production. Abiotic factors such as soil pH and alkalinity may influence the soil gas O\(_2\) concentrations. Higher pH and higher alkalinity soils will exhibit little CO\(_2\) in the soil gas due to the formation of carbonates. The soil water content will also impact the measurable CO\(_2\) in the soil gas due to the solubility of CO\(_2\).
3.5.1 Laboratory Testing

A series of analyses are generally performed on site soil samples to evaluate the potential for microbial degradation of the contaminants. The evaluations are conducted to determine whether the site soil samples have (1) a generally healthy microbial population without being stressed by the contaminant concentrations, and (2) specific microbial species capable of degrading the contaminants present. In addition, an analysis should be performed to determine the availability of soluble N- and P-containing nutrients such as ammonium, nitrate, and phosphates. Environmental parameters such as pH and moisture content should also be evaluated.

Total heterotrophic microorganisms and specific degrader microorganisms population is enumerated using the plate count procedure. At least $10^5$ colony forming units (CFU) per gram of soil should be present in the soil samples for bioventing to be feasible. Microbial population in the range of $10^7$ to $10^8$ CFU/gm of soil is considered very healthy for bioventing. Measurement of respiration rates can also be performed in the laboratory, using site soil samples, to evaluate the microbial activity.

In the past, biodegradability of specific contaminants was also evaluated in the laboratory. Currently, there is an abundance of data on biodegradability of common environmental contaminants (Appendix D).

3.5.2 Design of Bioventing Systems

The design of a bioventing system has three basic requirements. In order of importance, they are as follows:15,20

1. Maintain an oxygen flux through the contaminated soils matching the rates of active, aerobic biodegradation in those soils.
2. Maintain soil moisture within an optimal range for microbial activity.
3. Supply growth-limiting nutrients as needed to bolster microbial populations.

In order for these requirements to be satisfied, several operating parameters of a bioventing system need to be properly designed. These are discussed below.

3.5.2.1 Airflow Rate

It should be noted that there are different objectives for an SVE and a biovent system. An SVE system attempts to maximize airflow through the soil to maximize the rate of volatilization of contaminants into the air stream. A biovent system attempts to sufficiently manage the airflow rate to achieve maximum oxygen usage by the vadose zone microbial populations. Consequently, the biovent airflow rates are commonly an order of magnitude lower than SVE airflow rates. As a general rule of thumb, the air in the contaminated soil pore volume needs to be exchanged once every 1 to 2 days, depending on the air’s oxygen content.

Viable aerobic bioactivity is typically found in contaminated sites where the oxygen levels in the soil are above 2%. When the oxygen content of the soil air falls below 2%, aerobic bioactivity becomes dormant or absent. At this point the soil air is dominated instead by carbon dioxide and methane. In examining field data on vadose zone air quality, keep in mind that the soil air is made up of a large number of small-scale zones, or micro-zones, arrayed like a three-dimensional jigsaw puzzle determined by the geology and contaminant distribution. Within each micro-zone, the air can either be (1) replenished relatively frequently and is thus aerobically active, (2) replenished relatively infrequently and is thus aerobically dormant with high carbon dioxide levels, or (3) largely stagnant and active only anaerobically with accumulating products such as methane and carbon dioxide. Most monitoring or extraction wells intersect several of these micro-zones. If it intersects only the first type or only the third type of micro-zones described above, the results will seem clear-cut. If the well
intersects a mixture of micro-zone types, the results can be ambiguous and confusing. Typical O₂ and CO₂ percentages in the soil gas during bioventing are shown in Figure 3.41.

Well spacing is not the most important parameter for bioventing; rather, the airflow path is most important. The method is not reliant on the volatilization of contaminants for removal; rather, the introduction of oxygen for aerobic biodegradation to mineralize the contaminants. Consequently, the number of wells is often markedly fewer and in different locations than would be selected for an SVE system. These well locations are chosen to induce the flow of air with a high oxygen content across the area of contaminated soil.

3.5.2.2 Soil Moisture

For a bioventing system it is very important to maintain a moderate soil moisture, usually in the range of 40 to 60% of field capacity to maintain viable, aerobic bioactivity within the manipulated zone. If soil moisture increases appreciably above this range, the resultant pore sizes for air movement shrinks, decreasing the air permeability and flow rates. For these reasons, it is important to include in the design some means of adding moisture to the contaminated zone when necessary. It should be noted that impact of soil moisture on biodegradability is also influenced by the solubility of the contaminant.

Availability of O₂ is the rate-limiting step for bioventing in most cases. Optimum moisture content also plays a significant role, but not as dominant as the availability of oxygen. Macronutrients such as N and P and the micronutrients are generally available in the site soils. In rare cases, N and P containing soluble salts may have to be added to the site soils. Nitrogen and phosphorus initially consumed by the microbial mass are constantly recycled due to the lysis of dead microbial cells. Hence, the need and availability of N and P are critical only during the early stages of microbial growth.

3.5.2.3 Temperature

Temperature dependency of biodegradation rates have been reported to follow the van’t Hoff–Arrhenius equation,\textsuperscript{20,26,27} as well as the Phelps equation.\textsuperscript{20,27} The van’t Hoff–Arrhenius equation is as follows:

\[
Y = Ae^{-E_0/RT}
\]  

(3.35)
where $Y = $ temperature-corrected biodegradation rate
$A = $ baseline degradation rate
$E_a = $ activation energy
$R = $ gas constant
$T = $ absolute temperature.

The Phelps equation, which describes the relationship between respiration rate and temperature, is as follows:

$$R_t = R_7 \cdot \theta^{(t-7)}$$

where $R_t = $ rate at temperature $t^\circ C$
$R_7 = $ rate at $7^\circ C$
$\theta = $ thermal coefficient.

The design criteria of a bioventing system is summarized in Table 3.4.

<table>
<thead>
<tr>
<th>Table 3.4 Design Criteria for a Bioventing System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>1. Lateral and vertical extent of contamination</td>
</tr>
<tr>
<td>2. Geology of the contaminated zone</td>
</tr>
<tr>
<td>3. Air residence time and pore volume exchange</td>
</tr>
<tr>
<td>4. Location of air extraction wells, and air recharge conditions and the need for air injection wells</td>
</tr>
<tr>
<td>5. Soil moisture content and background nutrient levels</td>
</tr>
<tr>
<td>6. Continuous monitoring of $O_2$, $CO_2$, and other soil gas concentrations</td>
</tr>
</tbody>
</table>

### 3.5.3 In Situ Respiration Test

An in situ respiration test is perhaps the best method currently available to assess the rates of biodegradation that can be sustained by a bioventing system. This section describes the steps that are generally necessary for successfully carrying out an in situ respiration test.

#### 3.5.3.1 Equipment

The equipment needed for carrying out an in situ respiration test can be fairly simple. If an SVE pilot test is also to be carried out at the site, the test can make use of that pilot test equipment which is comparable to those listed below. Also, should a more rigorous test be required, some or all of the optional equipment can also be used. The basic equipment needed is listed below:

- Small air compressor or blower (a minimum of 1 to 2 cfm capacity). Examples of easily available equipment include car tire inflation pumps or air mattress inflation pumps. These can be plugged into a car cigarette lighter or other electric outlet.
- Oxygen ($O_2$) field monitoring device for air, with $\pm 0.5\%$ accuracy or less. Examples: Firite meter, explosimeter, Gastech meter.
- Carbon dioxide ($CO_2$) field monitoring device for air with $\pm 0.5\%$ accuracy or less.
- In-line sampling and field monitoring devices.
3.5.3.2 Test Procedures

1. Monitor the candidate wells for O₂, CO₂, CH₄, and total volatile organics concentrations in the adjacent vadose zone. Use the wells with at least a portion of their screen extending above the water table. Throughout these test procedures, remove several well casing volumes prior to collecting and analyzing samples.

2. Select a well for the test in a moderately contaminated area with predominantly aerobic bioactivity. Soil contaminant concentrations should be greater than 50 mg/kg. It is important to remember that, regardless of the conditions currently prevailing at the site, whether anaerobic, aerobic, or both, bioventing will ultimately convert the site to active, aerobic biodegradation. We must select those contaminated subareas of the site that can quickly and easily be converted to active, aerobic bioactivity during the test. Failure to select a proper test site will likely result in negative results.

3. Prior to beginning the test, measure the O₂, CO₂, CH₄, and total volatile organics concentrations in the test well.

4. Inject at least 1000 ft³ of air into the test well. Air can be injected in up to five wells. It is generally advisable to mix 1 to 2% He with the injected air as a tracer gas. Detection of He implies that the air sampled is the same that was injected and the changes in its makeup can be attributed to microbial activity. A volume of 1000 ft³ is deemed necessary to avoid boundary effects from interfering with the test results. Regardless of the capacity of the air pump used, this volume of air should be injected within 24 h. It usually takes about 24 h for the soil microbial populations to convert from their dormancy to active respiration. If a higher capacity pump is used, monitoring may optionally be carried out during the remainder of the 24-h period. However, the respiration rates monitored are typically distinctly lower than the respiration rates subsequently measured. At the least it provides a testing period for assessing the accuracy of the monitoring devices.

5. Begin periodic monitoring of O₂ and CO₂ concentrations in the test well 24 h following the start of air injection. Samples should be analyzed at least several times per day and, at most, hourly. The actual frequency should be selected in the field so that the data collected show a definite trend in O₂ and CO₂ concentrations in spite of the scatter caused by meter error.

6. Continue the monitoring of the test well until O₂ and CO₂ concentrations have changed at least 5%. Preferably, the test would be conducted until the O₂ and CO₂ concentrations have changed over 10%. This duration is necessary to define a definite trend through much of the range in O₂ concentration that active, aerobic biodegradation occurs. This will likely require a test duration of at least 1 day and possibly 2 days.

7. The data should be analyzed for both zero-order and first-order relationships. For zero-order analysis, compare the O₂ and CO₂ concentrations with respect to time (e.g., [O₂] vs. time). For first-order analysis, compare the ratio of the test O₂ and CO₂ concentrations to the initial concentrations with respect of time. Determine the linear regression equation for each analysis as well as the coefficient of determination (R²). Select the order of analysis that has the higher R² values. Previous studies have empirically found both approaches to be appropriate. Usually (but not always), the O₂ depletion trends have been found to be more reliable than CO₂ production trends. However, this is partly a function of the monitoring devices used and the geochemistry of the given site.

3.5.4 Modified Applications of Bioventing

3.5.4.1 Closed Loop Bioventing

It should be noted that 23.9 lb of oxygen can be introduced into the vadose zone in a day by introducing air at a flow rate of 1 scfm. At this rate of oxygen introduction into the vadose zone, all the oxygen present in the air will not be consumed by the microorganisms for contaminant biodegradation. As noted earlier, aerobic biodegradation of hydrocarbons require only about 3.5 g of oxygen per gram of hydrocarbons.

A closed-loop bioventing system, as shown in Figure 3.42, can be operated to maximize the percentage of contaminant mass biodegraded during system operation. Conceptually this
configuration utilizes the vadose zone soils as a bioreactor to degrade the contaminants. Continuous operation of the closed-loop system will eventually decrease the level of oxygen in the air extracted and reinjected. Hence, a partial discharge of the extracted air periodically or continuously will help in replenishing the amount of oxygen consumed by the microorganisms. The rate of this partial discharge does not have to exceed 10% of the total flow of the extracted air.

3.5.4.2 Bioventing with Pressure Dewatering

In this modified form of bioventing, air is injected into the vadose zone under pressure. The introduction of air pressure, locally, just above the water table (Figure 3.43), depresses
the water table, and this phenomenon is called pressure dewatering. The depression of the water table and subsequent gravity drainage, in turn, exposes the smear zone for increased levels of oxygen and thus faster rates of biodegradation in the capillary fringe. Faster removal of contamination in the capillary fringe and smear zone also helps in improving groundwater quality without direct groundwater remediation.

In addition the oxygen present in the injected air will enhance the biodegradation in the vadose zone. Caution should be provided to ensure the control of the migration of contaminant vapors beyond the zone of contamination, specifically into underground utilities and vaults.

### 3.5.4.3 Intrinsic Bioventing

This approach is discussed only at a conceptual level in this section. As noted earlier, a very low airflow rate will be sufficient to introduce the $3.5 \text{ g } \text{O}_2$ required per gram of hydrocarbons biodegraded. It is conceivable to design a system in which the positive pressure difference between the atmospheric pressure and the subsurface pressure caused by barometric changes (during the daytime) could be utilized to induce the airflow into the vadose zone. An automatic control system to induce the airflow into the vadose zone and close the reverse flow during nighttime will provide sufficient $\text{O}_2$ for enhanced biodegradation.

### 3.6 Monitoring Requirements

As noted earlier, the performance of an SVE system has to be optimized and fine-tuned continuously as the system operation proceeds. Monitoring data are used to assess system performance and calibration of models, and to guide necessary operational changes and equipment modifications.

The simplest way of assessing SVE process performance is to monitor the flow, vacuum responses and the concentration, and composition of the contaminants in the extracted air. This is the minimum monitoring required to identify mass removal rates and any changes in the subsurface conditions impacting the flow characteristics.

Table 3.5 presents an expanded list of monitoring requirements and the impacts on system performance.

### 3.7 Vapor Treatment Technologies

The most common technologies for treating air streams laden with volatile organic compounds (VOCs) are described briefly below. Types of common VOCs that require treatment when present in an air stream are as follows:

- aliphatic hydrocarbons
- aromatic hydrocarbons
- chlorinated hydrocarbons
- alcohols, ethers, and phenols
- ketones and aldehydes

Applicability of various vapor treatment technologies to the above contaminant types is shown in Table 3.6.

### 3.7.1 Thermal Oxidation

A tried and true technology for VOC control is oxidation, either catalytic or thermal. Oxidation units can destroy nearly 75% of the VOC and toxic emissions targeted by the Clean
Thermal oxidation, also known as thermal incineration, operates on a simple premise: sufficiently heating a VOC in the presence of oxygen will convert the VOC to harmless end products. During thermal oxidation, the VOC-laden air is captured by a ventilation system, preheated, thoroughly mixed, and combusted at high temperatures to form carbon dioxide and water. A thermal oxidation unit typically consists of a fan to move VOC-laden air; a filter–mixture to mix the VOC-laden air; a fan to supply combustion air (if required); a combustion unit consisting of a refractory-lined chamber and one or more burners; heat-recovery equipment; and a stack for atmospheric release of the treated exhaust. A continuous monitor is recommended to measure the combustion temperature to ensure complete oxidation.

Frequently, thermal oxidation systems require the use of supplemental fuel, such as natural gas or oil, to sustain the combustion temperature, which is nominally about 1200°F to 1600°F. Low-concentration VOC streams may not possess the oxidation energy required to maintain the combustion temperature; therefore, oxidation of these streams would require supplemental fuel or electrical energy. On the other hand, if exhaust streams contain very high concentrations of VOCs, dilution air may be required to prevent explosion.
Heat-recovery equipment may be installed with a thermal oxidation system to preheat the VOC-laden air stream prior to combustion. Preheating the incoming stream reduces the amount of supplemental fuel that would be required to maintain the combustion temperature.

In addition to combustion temperature, two other parameters that influence the VOC destruction efficiency of a thermal oxidation system are **residence time** and **degree of mixing**. Residence time is the amount of time required for complete oxidation of VOC. Generally residence time varies from 0.5 to 1 s. Longer residence times may be required if certain VOCs such as chlorinated organic compounds are present. The residence time is affected by the degree of mixing of VOC-laden stream prior to combustion. More thoroughly mixed VOCs require less residence time for complete oxidation.

There are three types of thermal oxidation systems: after-burners, recuperative, and regenerative. They are differentiated by the equipment used for heat recovery.

**Common after-burners** utilize a direct-fired burner(s) in an insulated combustion chamber sustaining a temperature of 1500°F for at least 0.5 s. They have no heat-recovery equipment. The burning chamber will be sized to allow for the given residence time at a certain airflow velocity. This system has the lowest capital cost but is the most expensive to operate. High VOC concentrations will help minimize auxiliary fuel consumption.

**Recuperative systems** (Figure 3.44) use a heat exchanger, typically crossflow, counterflow, or concurrent flow, for heat recovery. The heat exchanger is the heart of this technology. The VOC-laden air stream is preheated to a maximum of approximately 80% of the 1500°F combustion temperature. This system is sized based on the flow rate, and the cost will go up in proportion to the efficiency and number of passes being made in the exchanger. The recuperative system is best suited for moderately high VOC concentrations and can tolerate a broad mix of constituents. But if the design VOC concentration is reduced or if there are swings in incoming VOC concentrations, the auxiliary fuel consumption will go up dramatically.

**Regenerative systems** use ceramic material for heat recovery. The ceramic material is stored in separate beds that feed to a central combustion chamber. They generally use less supplemental fuel than the other systems because of the superior heat transfer capability of the ceramic material. As a result, these systems may be attractive for controlling low VOC streams.

During thermal oxidation of chlorinated hydrocarbons, hydrochloric acid (HCl) fumes are formed in addition to CO₂ and H₂O. As a result, removal of the HCl formed is necessary before the treated air is discharged to the atmosphere. A scrubber installed before the stack will facilitate the removal of the acid present in the effluent air stream prior to discharge. Caustic soda or potash can be used as the absorbent solution in the scrubber. Less than perfect combustion of the VOCs may lead to solubilization of the residual VOCs in the scrubbing
solution. Care should be taken to dispose the neutralized scrubbing solution properly under these circumstances.

In summary, the design criteria for thermal oxidation is governed by

- influent airflow rate
- VOCs concentration
- VOCs stream composition
- influent stream fuel value
- combustion temperature
- residence time
- degree of mixing
- oxygen content of flue gas

### 3.7.2 Catalytic Oxidation

Catalytic oxidation is very similar to thermal oxidation and combines a conventional-type heat exchanger with a catalyst. A catalyst inside the combustion unit lowers the activation energy for combustion; thus, combustion occurs at a lower temperature than for thermal oxidation. The catalyst, either precious or base metal, will allow oxidation to occur at a fairly low temperature of about 500°F to 700°F. As a result, fuel costs for catalytic oxidation are usually much lower than for an equally applicable thermal oxidation system. In the absence of centralized gas supply or under safety restrictions for flame combustion, electric power may be a convenient means to heat the influent air stream.

Typical catalyst materials include platinum, palladium, and metal oxides such as chrome-alumina, cobalt oxide, and copper oxide–manganese oxide. The average catalyst lifetime is 2 to 5 years, after which deactivation by inhibitors, blinding by particle entrainment, and thermal aging render the catalyst ineffective. Catalytic materials may be inserted into the combustion unit in either a monolithic or beaded configuration.

Because of its sensitivity to VOC-laden air streams and process operating characteristics, the catalyst dictates the optimum operating conditions for a catalytic oxidation system (Figure 3.45). There is an inverse relationship between conversion efficiency and process flow rates. The higher the conversion efficiency desired, the lower the flow rate that can be processed. Higher flow rates require the installation of multiple catalysts.

![Schematic diagram of a catalytic oxidizer.](image-url)
Catalytic oxidation systems are not effective in streams containing lead, arsenic, sulfur, silicone, phosphorus, bismuth, antimony, mercury, iron oxide, tin, zinc, and other catalyst deactivators. These compounds have a tendency to mask or poison the catalyst’s cell structure. When this occurs, the catalyst’s ability to react chemically with the hydrocarbon decreases, requiring more fuel to rise to a temperature where proper oxidation will take place. Masking of the catalyst may also cause airflow restrictions whereby more horsepower could be needed to push the air through the system. In order to prolong the lifetime of the catalyst, it has to be cleaned periodically to remove deactivators and particulates.

Catalytic oxidation systems are typically applied to low-VOC-concentration streams, since high VOC concentrations and associated high heat contents can generate enough heat of combustion to deactivate the catalyst. Dilution air may be required when the influent VOC concentrations are high. The temperature and pressure across the catalyst bed should be monitored to ensure catalyst viability. The temperature rise across the catalyst indicates the extent of VOC oxidation; a decrease in the temperature rise across the catalyst indicates that VOC oxidation is incomplete. Since excessive heat can deactivate most catalysts, the inlet temperature to the catalyst bed must be kept sufficiently low to preserve catalyst activity. Similarly, the pressure drop across the catalyst is also an indication of the catalyst bed viability. The substantial amount of process control required to operate a catalytic oxidizer is illustrated in Figure 3.46.

Design criteria for catalytic oxidation systems can be summarized as follows:

- influent airflow rate
- influent stream composition
- influent VOCs concentration
- operating temperature
- catalyst properties
- space velocity and retention time
- influent stream fuel value
- oxygen content of flue gas
- presence of impurities and poisoning compounds
- type of heat exchanger
- availability of energy source (electricity vs. natural gas)

### 3.7.3 Adsorption

Adsorption refers to the process where gaseous VOC molecules contact a solid adsorbent and bond via weak intermolecular forces. Activated carbon is the most common adsorbent in use today for VOC removal. Other adsorbents include silica gel, alumina, and specialized resins. Activated carbon is derived from wood, coal, or other carbonaceous raw materials such as coconut shells. Granular activated carbon is currently the most common type of carbon used for VOC abatement, because the granules contain a significant amount of available surface area. Powdered activated carbon is generally cheaper and of lower quality than granular activated carbon, and when used in packed columns may cause unacceptably high pressure drops. Additionally, powdered activated carbon is nonregenerable, and must be disposed once it is spent. Granular activated carbon prepared from coconut shells can be prepared in large particle sizes necessary to help minimize pressure drop and is extremely hard, which leads to low attrition even under rough handling and high gas velocity conditions.

The adsorption of VOCs on the micropore surfaces of carbon is mainly a physical process involving van der Waals type forces and involves the liberation of from 2 to 5 kcal/mol of heat. Since these interactions are weak, the VOC is in dynamic equilibrium with the carbon surface and is being constantly adsorbed and desorbed. This adsorption/desorption
process causes the VOC to be retained in the carbon pore structure. The more the VOC is “like” the carbon surface, the stronger it will interact with the surface. For example, molecules consisting mainly of aromatic or aliphatic moieties will adsorb more strongly than oxygenated molecules.

Vapor-phase granular activated carbon is generally used in a fixed bed, and the contaminated air is passed through the adsorbent bed. The adsorption of VOCs from air by a carbon bed is a continuous process, but for convenience of presentation can be envisioned as taking place in layers. Thus one can envision that when a contaminant stream passes through the bed, some contaminant is removed by layer “a” at the entrance of the bed, leaving a lower contaminant level in the stream to contact the next layer “b”. Layer “b” then in turn removes more of the contaminant. The reduction of contaminant level as the

Figure 3.46 Catalytic oxidizer piping and instrumentation diagram.
stream contacts further layers of unused carbon continues until finally layer “z” is reached. The layers of “a” to “z” are known as the adsorption zone or the mass transfer zone (MTZ). As the flow continues, the MTZ progressively advances and propagates until breakthrough occurs. The following factors play important roles in adsorption dynamics and the length and shape of MTZ.

- Type, size, and macro- and micro-pore surface area of the carbon
- Depth of the adsorbent bed and empty bed contact time
- Gas velocity
- Temperature of the influent air stream
- Concentration of contaminants to be removed
- Moisture content and relative humidity
- Pressure of the system
- Vapor pressure of the contaminants to be adsorbed
- Possible decomposition or polymerization on the carbon surface.

Adsorption decreases with increasing temperature. Because the equilibrium capacity of adsorbents is lower at higher temperatures, the dynamic or breakthrough capacity will also be lower, and the MTZ proportionately changes with temperature. It should be also noted that the adsorption process is exothermic. As the adsorption front moves through the bed, a temperature front also proceeds in the same direction, and some of the heat is imparted to the gas stream. When the gas leaves the adsorption front, the heat exchange will reverse and the gas will impart heat to the bed. This increase in temperature in downgradient zones in the bed decreases the capacity in that zone. As a result, the maximum inlet concentration to a carbon bed should be limited to less than 10,000 ppmv.

The relative humidity and the moisture content of the influent stream also have a significant impact on the adsorption capacity of the bed. Small quantities of moisture actually enhance the adsorption process, as the heat of adsorption is carried with the moisture. However, relative humidities in excess of 50% tend to lessen the effectiveness of the bed. Moisture knockout systems or in-line heaters installed upstream of the bed will help to alleviate this problem. Moisture content plays an important role when treating effluent air streams of an air stripper. Polymeric adsorbent resins which are significantly more hydrophobic than carbon have shown to be able to adsorb at least 10 times more VOC mass than activated carbon.

When using activated carbon for air treatment, the spent carbon must be replaced or regenerated. If the replacement option is chosen, as soon as the carbon is spent it is removed and sent to an off-site reprocessing facility to be regenerated. Removal of the spent carbon from the bed and introduction of new carbon is accomplished as a wet slurry. This option is preferred when the total mass of VOCs to be removed during the life of the project is not high.

When the contaminant mass to be removed is high, either during short-term or long-term operations, fixed regenerative beds may be the preferred mode. On-site regenerative beds consist of two or more beds of activated carbon. Continuous operation of the system is maintained by the concurrent adsorption in at least one bed and desorption by the other beds. A schematic diagram of a fixed regenerative carbon bed is shown in Figure 3.47.

Desorption of the carbon bed refers to the process or regenerating the carbon to restore its adsorbing capabilities and preserve its useful life (usually 2 to 5 years). The desorption process normally lasts 1 to 2 h and consists of the following three steps: regeneration of the carbon, bed drying, and returning the bed to its operating temperature. Carbon regeneration is accomplished by volatilizing the adsorbed compounds either by raising the temperature of the carbon bed via steam (steam desorption) or lowering the temperature in the bed to vacuum conditions to increase the vapor pressure of the adsorbed VOCs (vacuum desorption). The adsorption time of each bed is dependent on the influent mass.
flux rate and is usually finalized during the installation and start-up period. The automatic cycling of beds between adsorption and desorption modes is controlled by an onboard programmable logic controller.

When chlorinated organic compounds are present, HCl may be produced during steam regeneration of the carbon beds. Accumulation of HCl in the beds may corrode the container and require periodic replacement. Under such circumstances, use of a container that has a corrosion-resistant internal surface such as Teflon or Hazaltloy should be used. Another method of overcoming the same concern is to use heated nitrogen as a carrier gas under vacuum desorption conditions. Nitrogen also helps in maintaining an inert environment in the bed. The nitrogen containing all the purged VOCs is condensed, and the VOCs are separated as a liquid before reusing the nitrogen gas.

When the influent air stream flow rates are small and the total VOC mass is less, smaller-sized carbon canisters that are usually of 55 gal in volume and contains approximately 200 lb of carbon can be used. Once the carbon becomes saturated, these canisters are disposed and replaced with a new canister.

Carbon adsorption is not effective for controlling highly volatile VOCs (such as vinyl chloride), which do not adsorb well. Similarly, highly nonvolatile VOCs (compounds with very high molecular weight) which do not desorb well are also not good candidates for removal by carbon adsorption.

Design criteria for carbon adsorption systems can be summarized as follows:

- influent airflow rate
- influent stream composition
- influent VOCs concentration and total mass
- adsorption capacity
- influent air temperature
- influent air moisture content and relative humidity
- adsorption equilibria related to waste mix

### 3.7.4 Condensation

Condensation is the process of removing VOCs from a noncondensable gas stream. Condensation can occur by lowering the gas stream temperature at constant pressure or increasing the gas stream pressure at constant temperature (or a combination of both).30

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There are two popular types of condensers: surface and direct contact. Surface condensers are generally shell and tube heat exchangers where coolant flows inside the tubes to condense the VOCs in the gas stream flowing outside the tubes. Contact condensers operate by spraying a cool liquid directly into a gas stream to cool it and condense the VOCs. In both types of condensers, the VOCs may be reused or disposed. Excessive influent moisture content will impact the process by ice formation. Removal of moisture prior to condensation may be required under those circumstances.

Coolants used to condense VOCs include chilled water, brine solutions, chlorofluorocarbons (CFCs), and cryogenic fluids. Chilled water is an effective coolant down to approximately 45°F. Brine solutions are effective coolants down to approximately –30°F. CFCs are effective coolants down to approximately –90°F. However, the production and use of most CFCs are expected to be eliminated by the year 2000. Cryogenic fluids, mainly liquid nitrogen or carbon dioxide, can be effective down to temperatures as low as –320°F. Figure 3.48 is a schematic diagram of a typical condensation system.

Design criteria for condensation systems are as follows:

- influent airflow rate
- stream composition
- required condensation temperature
- mixture dew point
- moisture content in influent stream

### 3.7.5 Biofiltration

Biofiltration, a well-established technology in Europe, is just starting to get noticed in the U.S. Biofiltration harnesses the natural process of contaminant degradation with immobilized microorganisms. In a biofilter, the microorganisms grow on materials such as soil, compost, peat, or heather, supplemented sometimes with synthetic materials including activated carbon (to adsorb certain VOCs) and polystyrene, which provides bulking and structural stability. Recent designs tend to favor mineral soils and synthetic mixtures designed for durability and good retention of moisture and structural characteristics. Biofiltration beds may be open to the atmosphere or enclosed. Single-bed or multiple-stack configurations are available. Figure 3.49 presents a schematic diagram of a closed, single-bed biofiltration system.

In a biofiltration system, the VOC-laden airstream is dedusted, cooled, or humidified as necessary and then transported via a blower and a network of perforated piping into the beds which contain immobilized microorganisms. As the VOCs enter the biofilter, they diffuse into the biofilm, where the microorganisms oxidize them to carbon dioxide water and chloride (in the case of chlorinated VOCs). The oxygen present in air also diffuses into the biofilm.
to facilitate the aerobic microbial metabolism. The residence time of the air stream depends on such factors such as the composition of the waste stream and its flow rate. The process takes place entirely in the biofilm: no contaminants are permanently transferred to the filter material. The microorganisms at the heart of biofiltration can be native to the soils used in the bed or specially cultured microorganisms adapted to the specific VOCs. Most biofiltration systems can be acclimatized to the target air stream in about 2 to 3 weeks, either with native microorganisms or specialized microbial species. Biofilters are an especially good candidate to treat air streams which contain biodegradable compounds such as alcohols, ketones, ethers, esters, organic acids, and lighter end petroleum compounds. Some of chlorinated organic compounds (such as methylene chloride and chlorobenzene) can also be treated with the practical residence times available.

As mentioned earlier, pretreatment of the VOC-laden air stream is important for preserving the longevity of the filter bed. Dust particles in the air stream can clog the piping and the filter bed, thus increasing the pressure drop and reducing available sites for biofilm growth. Cooling of the air stream to the optimum operating temperature of approximately 30°C to 40°C is required to prevent deactivation of the microorganisms. Humidification of the incoming air stream is important to maintain the required moisture content.

A consistent moisture level (the correct level depends upon the type of filter material) is essential for biofilter effectiveness. The microorganisms require a moist environment to maintain a viable biofilm and, clearly, blowing air on damp filter material is going to have a drying effect. In addition, the filter must be consistently kept moist to prevent cracking due to repeated drying and wetting. Cracks formed in the bed would permit escape of untreated VOCs to the atmosphere. Moisture can be controlled by humidification as a pretreatment step or by moisturizing the filter bed with spray nozzles (Figure 3.49).

Design criteria for biofiltration systems are summarized below:

- influent airflow rate
- stream contaminant composition (biodegradability of contaminants)
- influent contaminant concentrations
- required pretreatment
- available residence time
- influent temperature
- space requirements
- filter size
- filter bed material

### 3.7.6 Membrane Filtration

Membrane filtration technology refers to the use of a semipermeable membrane to separate VOCs from an air stream. Membrane technology has been found to be effective in removing some VOCs that traditionally have been difficult to recover, such as chlorinated hydrocarbons and CFCs. In this process, VOC-laden air contacts one side of a membrane that is permeable to organic vapors but is relatively impermeable to air. A partial vacuum, applied on the other side, draws the organic vapors through the membrane. The permeate vapor is then compressed and condensed to recover the organic fraction. The purified air stream is removed on the feed side.

The membrane unit, shown in Figure 3.50, is a spirally wound module comprised of a perforated pipe bound within the wound membrane and spacers. In the system shown in Figure 3.50, VOCs in a compressed air stream enter the first of two membrane stages. The first stage concentrates most of the VOCs into the permeate stream. The permeate is recompressed and condensed, normally producing only water present in the air stream as moisture. The bleed stream leaving the condenser enters the second membrane stage, reducing the VOC content.
The permeate from this stage is concentrated enough with VOCs to allow for its condensation. The bleed stream from this condenser is recirculated back to the first stage membrane unit. In its entirety, the system separates the VOC-laden air stream into a VOC-depleted stream and condensed liquid VOCs.

Figure 3.49 Components of a biofiltration system. (After Vembu, K. and Walker, C. S., Biofiltration holds VOCs, odors at bay, Environ. Prot., February 1995.)

Figure 3.50 VOC removal in air streams by membrane separation.

Further. The permeate from this stage is concentrated enough with VOCs to allow for its condensation. The bleed stream from this condenser is recirculated back to the first stage membrane unit. In its entirety, the system separates the VOC-laden air stream into a VOC-depleted stream and condensed liquid VOCs.
3.7.7 Cost Considerations

Capital and annualized costs of vapor treatment technologies are fundamental to the selection of a specific technology. Clearly, a treatment technology that proves to be overwhelmingly expensive for the amount of VOCs to be treated will be eliminated early in an equipment selection process.

As fundamental as costs are to equipment selection, they are also very unit-specific, because of their dependence on unique stream characteristics such as flow rate, VOCs composition and concentration, and operating temperature. It is presumptuous to conclude that a cost estimate for a particular treatment technology based on a specific set of operating conditions can be applied universally to every other possible set of operating conditions.

Another important aspect to consider during design of subsurface remediation system is the expected decline of VOC concentration in the air stream during the life of the project. A particular technology that may be very cost-effective during the initial, high-concentrations phase may not be cost-effective as the concentrations decline. A break-even analysis should be performed by including the capital costs, operating costs, and the impact on operating costs due to the decline of VOCs concentration in the air stream to be treated. An example of such an analysis performed for three technologies for a specific stream is shown in Figure 3.51. The other technologies were eliminated during the initial screening process.

Energy required to operate the systems is the major component contributing toward the annual operating costs. Availability of a specific energy source may have a significant impact on the operating cost. For example, propane is 1.5 times more expensive than natural gas, and electricity is 3.5 times more expensive than natural gas.

REFERENCES