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Estimation of Effective Cleanup Radius for Soil-Vapor Extraction Systems

David H. Bass, Sc.D., CHMM

Groundwater Technology, Inc., 3 Edgewater Drive, Norwood, MA 02062

ABSTRACT: Soil-vapor extraction (SVE) is a standard and effective *in situ* treatment for the removal of volatile contaminants from vadose-zone soil. The duration of SVE operation required to reach site closure is quite variable, however, ranging up to several years or more. An understanding of the contaminant recovery rate as a function of distance from each vapor-extraction well allows SVE systems to be designed so that cleanup goals can be achieved within a specified time frame.

A simple one-dimensional model has been developed that provides a rough estimate of the effective cleanup radius (defined as "the maximum distance from a vapor extraction point through which sufficient air is drawn to remove the required fraction of contamination in the desired time") for SVE systems. Because the model uses analytical rather than numerical methods, it has advantages over more sophisticated, multidimensional models, including simplicity, speed, versatility, and robustness.

The contaminant removal rate at a given distance from the vapor-extraction point is assumed to be a function of the local rate of soil-gas flow, the contaminant soil concentration, and the contaminant volatility. Soil-gas flow rate as a function of distance from the vapor-extraction point is estimated from pilot test data by assuming that the infiltration of atmospheric air through the soil surface is related to the vacuum in the soil. Although widely applicable, the model should be used with some caution when the vadose zone is highly stratified or when venting contaminated soil greater than 30 ft below grade. Since 1992, Groundwater Technology, Inc. has been using this model routinely as a design tool for SVE systems.

KEY WORDS: soil-vapor extraction, modeling, design tool, effective radius.

I. BACKGROUND

Soil-vapor extraction (SVE) is a widely used *in situ* remediation technique for treatment of contaminated vadose-zone soil. SVE removes volatile organic compounds (VOCs) from vadose-zone soils by inducing air flow through contaminated areas. SVE is typically performed by applying a vacuum to vertical vapor-extraction wells screened through the level of soil contamination, using a vacuum blower. The resulting pressure gradient causes the soil gas to migrate through the soil pores toward the vapor-extraction wells. VOCs are volatilized and transported out of the subsurface by the migrating soil gas. In addition, SVE increases oxygen flow to contaminated areas, thus stimulating natural biodegradation of aerobically degradable contaminants.

The performance of SVE systems improves as the air permeability of the vadose-zone soil increases. SVE is applicable to any compound with a vapor pressure greater than about 1 mmHg. This includes a wide variety of common contaminants such as benzene, toluene, ethylbenzene, xylene, gasoline hydrocarbons, mineral spirits, methyl *t*-butyl ether, tetrachloroethylene, trichloroethylene, 1,1,1-trichloroethane, methanol, acetone, and butanone. Because vapor pressure increases with temperature, SVE also can be applied to semivolatile compounds by heating the vadose zone with steam or hot air.

The efficacy of a SVE system is determined by its ability to draw sufficient air through the contaminated portion of the vadose zone. The number and spacing of vapor-extraction wells and the soil-gas extraction rate are the critical parameters determining air flow through the subsurface. In addition, several modifications to SVE systems are sometimes used in an effort to enhance the flow of air through the contamination zone. These include air injection (forcing air or allowing air to be drawn through wells screened at the level of the vadose-zone contamination) and surface sealing (paving a surface or covering an unpaved surface with a layer of polyethylene film to prevent infiltration of air and water from the surface).

Vapor-extraction well spacing is typically determined by performing a field pilot test to determine the radius-of-influence (ROI) at the site under specified SVE conditions. Historically, pilot test data were interpreted by assessing the distance from the vapor-extraction well where an arbitrary vacuum level (usually 0.01 to 1 in of water column) could be measured in the soil. Although such “rules of thumb” often result in adequate SVE system design, they do not yield any information on the quantity of air moving through the vadose zone. This approach, therefore, cannot provide any assessment of remediation time, nor can it provide design information specific to the contaminant (a system designed to remove benzene will be less effective on the less volatile xylene, for example).

Several alternative approaches to interpretation of SVE pilot test data have recently been developed based on multidimensional modeling of vacuum and soil-gas flow fields in the vadose zone. Johnson *et al.* (1990a, 1990b) derived equations describing air flow in the vadose zone beneath a sealed surface and applied these equations to the SVE remediation of gasoline contaminated soil. Baehr *et al.* (1989) and Marley *et al.* (1990) and others have used numerical solutions for systems with unsealed or partially sealed surfaces, and Lingineni and Dhir (1992) superimposed variable temperature on this approach. Joss and Baehr (1993) have recently adapted MODFLOW, a groundwater numerical modeling program, to SVE applications.

II. MOTIVATION AND OBJECTIVES

The modeling efforts discussed in the previous section represent important advances in the understanding of SVE and provide a basis for more effective design of SVE systems. However, they are not universally applicable. The data available at many small sites where SVE is considered, such as retail gasoline stations and dry cleaning facilities, are often sparse, and budgets rarely exist for gathering the more extensive data required for sophisticated models. Most of these sites have been repeatedly excavated and refilled, creating subsurface anisotropies that confound the limited data. Furthermore, many of the models assume that the surface is sealed, a condition not commonly encountered (and sometimes not even feasible) at such retail sites. Finally, multidimensional models typically require substantial time to input variables and to run, making the design process tedious.

Therefore, the need exists for a model that can provide rapid order-of-magnitude assessments of potential SVE performance based on very limited data. For this application, a simpler one-dimensional model is adequate; the data quality is ordinarily too poor and the subsurface too laden with unidentified anisotropies to warrant a more sophisticated, multidimensional approach. To be most useful, such a model must exhibit the following characteristics:

- Simplicity: cumbersome computer models are intimidating and tend not to be used; a really useful model must be readily accessible by the most junior of engineers.
- Speed: instantaneously, solutions enable an engineer to apply many “what if” scenarios in a short period of time, and hence rapidly converge on an optimum design.
- Versatility: depending on the specific project requirements, the model may be called on to specify SVE well spacing, soil-gas extraction rate, cleanup level, or cleanup time at sites with sealed or unsealed surfaces.
- Robustness: the model must provide reasonable estimates of SVE performance over wide ranges of soil permeability, soil-gas extraction rate, soil temperature, and contaminant volatility.

III. MODEL DERIVATION

The goal of the model is to determine the maximum distance from the vapor-extraction well through which sufficient air is drawn to remove the required fraction of contamination in the desired time. This is the effective radius, R_E, and it differs from the ROI, which is the distance from the vapor-extraction well that vacuum can be detected. The effective radius is based on site-specific conditions and SVE system parameters, and it is specific to the contaminant, cleanup goals, and cleanup time frame.

This derivation is applicable to sites with unsealed surfaces and single-well SVE systems or multiple-well systems in which each well is operated individually, rather than simultaneously (as if often done when surface infiltration of air is insufficient to achieve adequate remediation between vapor-extraction wells). This approach has also been extended to simultaneously operated multiple-well systems and to sites at which an engineered surface seal is to be applied, and these will be the subject of future publications.

Figure 1 illustrates the general air-flow patterns through soil during SVE. Because this derivation is for a single-well SVE system, it is assumed that the effective radius will extend to the edge of the contaminant plume. At the outer edge of the plume, all air entering the contamination zone is initially uncontaminated. As the air flows through the soil, contaminants rapidly equilibrate between soil and air phases (the rapid approach to equilibrium was demonstrated by Johnson *et al.,* 1990a). This equilibration is determined by contaminant-soil concentration, vapor pressure, and water solubility, and by the moisture and organic content of the soil. Of these parameters, only the contaminant soil concentration changes dramatically during the course of the vapor extraction, and so for a given site and contaminant, the equilibrium-gas concentration can be expressed generally as a function of soil concentration:

$$C_g = f\left(C_s\right) \tag{1}$$

The rate at which contaminant mass is lost from soil must equal the rate at which the soil gas flowing through the soil carries the contamination away:

$$\frac{dM_s}{dt} = \frac{d\left(V_s C_s\right)}{dt} = C_g q = f\left(C_s\right)q \tag{2}$$

or

$$\frac{dC_s}{f\left(C_s\right)} = \frac{q}{V_s}\,dt \tag{3}$$

where M_s = mass rate of contaminant removal from soil, t = time, V_s = volume of soil (control volume), q = flow rate of gas through control volume.

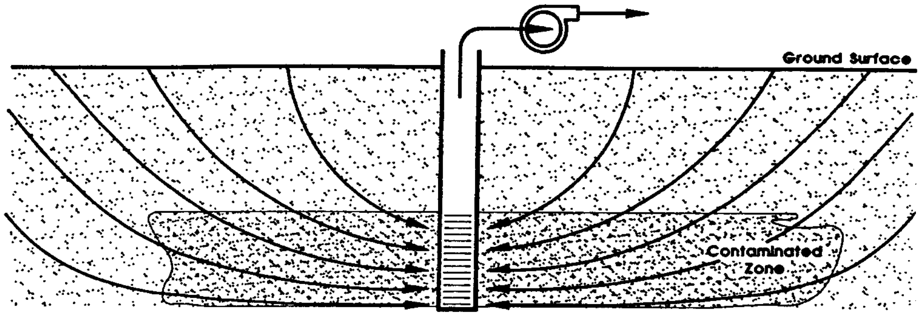

FIGURE 1. Generalized air flow paths in a soil-vapor extraction system.

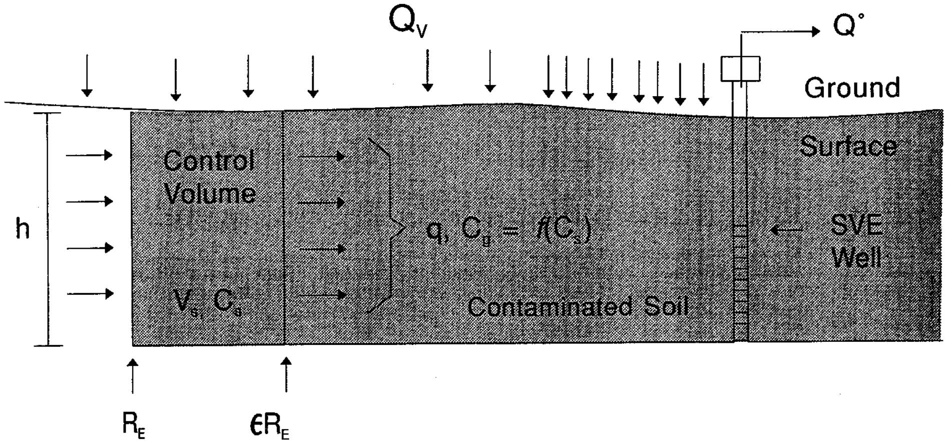

FIGURE 2. Conceptualization of the model. The system is to be designed so that the effective radius, R_E, corresponds to the extent of contamination. Clean air enters the contaminated zone by horizontal movement through the soil and by vertical infiltration through the ground surface. The overall cleanup time is dominated the remediation rate for the contaminated soil between εR_E and R_E (“control volume”), which is determined by the air flow rate, q, through this portion of the contaminated zone.

The contaminated zone is represented as a uniform cylinder of radius R_E and height h, as indicated in Figure 2. Remediation will occur from the outside of the plume inward (due to lateral introduction of uncontaminated air into the contamination zone) and from the top down (due to vertical infiltration of air). Although the outermost portion of the contamination zone will be treated first, the rate of treatment at this location will be the slowest because the air flux decreases rapidly with distance from the vapor-extraction well. The control volume is therefore taken as a fraction of the contamination zone furthest from the vapor-extraction well, that is, an annulus of outer radius R_E and inner radius εR_E, where $O < \varepsilon < 1$.* The control volume is then

$$V_s = \pi\left(R_E^2 - \left(\varepsilon R_E\right)^2\right)h = \left(1 - \varepsilon^2\right)\pi R_E^2 h \tag{4}$$

The gas flow through the control volume, q, is calculated by assuming that, at a distance r from the vapor-extraction well, any infiltration of atmospheric air through the soil surface is related to the vacuum in the soil and the area of the ground surface:

$$dQ_v = k_v\left(P_a^2 - P_r^2\right) dA = k_v\left(P_a^2 - P_r^2\right)2\pi r\, dr \tag{5}$$

where Q_v = vertical infiltration of atmospheric air, r = distance from the vapor extraction well, P_a = absolute atmospheric pressure, P_r = absolute pressure at distance r from the vapor-extraction well, k_v = constant, A = area of ground surface. The term $k_v(P_a^2 - P_r^2)$ comes from Darcy's Law for flow of a compressible fluid. The constant k_v is related to the permeability of the soil to vertical gas infiltration, as well as to the gas viscosity, density, and travel distance.

Because all the air collected at the vapor-extraction well must come ultimately from the atmosphere through the ground surface, the integral of Equation 5 from the well radius to the radius of influence yields the rate of total soil-gas recovery, Q^o:

$$\int_{r_w}^{R_I} dQ_v = 2\pi k_v \int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\, dr = Q^o \tag{6}$$

where r_w = radius of vapor-extraction well, R_I = radius of influence.

Substituting Equation 6 into Equation 5 and integrating again, this time from the well radius to the inner edge of the control volume, yields

$$\frac{Q_v}{Q^o} = \frac{\int_{r_w}^{\varepsilon R_E} \left(P_a^2 - P_r^2\right) r\, dr}{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\, dr} \tag{7}$$

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* The value of the parameter ε is selected so that vertical infiltration at distances less than εR_E from the vapor-extraction well provides a rate of remediation at least comparable with the remediation rate within the control volume due to lateral and vertical introduction of clean air. In other words, by the time the control volume is clean, the rest of the contaminated zone will have been remediated as well. For most sites where SVE is considered, ε ranges from 0.7 to 0.9. Within this range, the precise value of ε selected is not crucial, because values of R_E computed from the design equation derived later are not particularly sensitive to changes in ε, varying typically by 10% or less.

The gas passing through the control volume is the total gas flow collected less the vertical infiltration that occurs closer to the SVE well

$$q = Q_v^o - Q_v = Q_v^o \frac{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\,dr - \int_{r_w}^{\varepsilon R_E} \left(P_a^2 - P_r^2\right) r\,dr}{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\,dr} \tag{8}$$

Combining Equations 3, 4, and 8 and integrating yields

$$\int_{C_s}^{C_s^o} \frac{dC_s}{f\left(C_s\right)} = \frac{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\,dr - \int_{r_w}^{\varepsilon R_E} \left(P_a^2 - P_r^2\right) r\,dr}{\left(1 - \varepsilon^2\right) \pi R_E^2 \int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\,dr} \frac{Q^o t}{h} \tag{9}$$

where C_s^o = initial contaminant concentration in the soil.

Whenever $dC_s/f(C_s)$ and $P_r^2 r\,dr$ are analytically integrable, Equation 9 provides a vehicle for relating the effective radius (R_E) to soil concentration in the control volume (C_s), soil-gas recovery rate (Q^o), and remediation time (t) without the use of cumbersome numerical methods. Depending on site-specific conditions, any of a number of expressions for P_r and $f(C_s)$ are appropriate.

For example, Johnson *et al.* (1990a) derived the following expression for P_r, which is applicable when the ground surface is sealed:

$$P_r^2 = P_w^2 + \left(P_a^2 - P_w^2\right) \frac{\ln\left(r / r_w\right)}{\ln\left(R_I / r_w\right)} \tag{10}$$

where P_w = absolute pressure in the vapor extraction well.

When the ground surface is not sealed, P_r can be approximated by the following simple exponential relationship over a substantial range of distances from the vapor-extraction well (i.e., when r is greater than a few feet) (Mohr, personal communication, 1992):

$$\ln\left(P_r\right) = c_1 r + c_2 \tag{11}$$

where c_1 and c_2 are fitted constants.

At lower soil concentrations, it is proper to assume ideal partitioning between soil and gas ($f(C_s) = K_{gs}C_s$), whereas above a compound-specific threshold soil concentration, vapor concentration becomes independent of soil concentration

(Lyman *et al.,* 1990); under such conditions, $f(C_s)$ is simply the contaminant saturated-vapor density and is constant. More complex representations of $f(C_s)$ are required for soil contaminated with a diverse mixture of compounds, such as gasoline. As SVE proceeds, the more volatile species are preferentially removed and the remaining contamination becomes less volatile. Therefore, $f(C_s)$ must decrease as C_s decreases, and this effect is demonstrated in Figure 3 for fresh and weathered gasoline. As is evident from the figure, the decrease in $f(C_s)$ with decreasing C_s is roughly exponential.

IV. MODEL IMPLEMENTATION AND LIMITATIONS

Equation 9 contains the following parameters:

- gas-soil equilibrium relationship ($f(C_s)$), which is a function of soil-gas temperature and contaminant volatility
- pressure as a function of distance from the vapor-extraction well (P_r), which is a function of vapor-extraction well pressure (P_w) if Equation 10 is used the fitted constants c_1 and c_2 if Equation 11 is used
- depth of vented interval (h)[†]
- soil-gas recovery rate (Q^o)
- treatment time (t)
- effective radius (R_E)
- vapor-extraction well radius (r_w)
- radius of influence (R_I) and
- extent of remediation ($1 - C_s/C_s^o$).

Equation 9 can be evaluated to solve for any of these variables, provided all others are specified. The model has been implemented in a computer program written in Basic that prompts the user to choose which variable to solve for (effective radius, cleanup time, extent of remediation, or soil-gas recovery rate). The user then

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[†] The vented interval is the portion of the vadose zone through which air movement is induced during SVE. If the vadose zone is fairly homogeneous, air movement will be induced throughout, and it is appropriate to consider the vented interval to be the depth to the bottom of the vapor-extraction well. When the vadose zone is stratified, each contaminated stratum is vented separately. If a contaminated low permeability stratum underlying a clean higher permeability stratum is being vented, the vented interval should be considered to be the thickness of the low permeability stratum. This approach is not applicable, however, for a higher permeability stratum underlying a substantial, continuous lower permeability stratum.

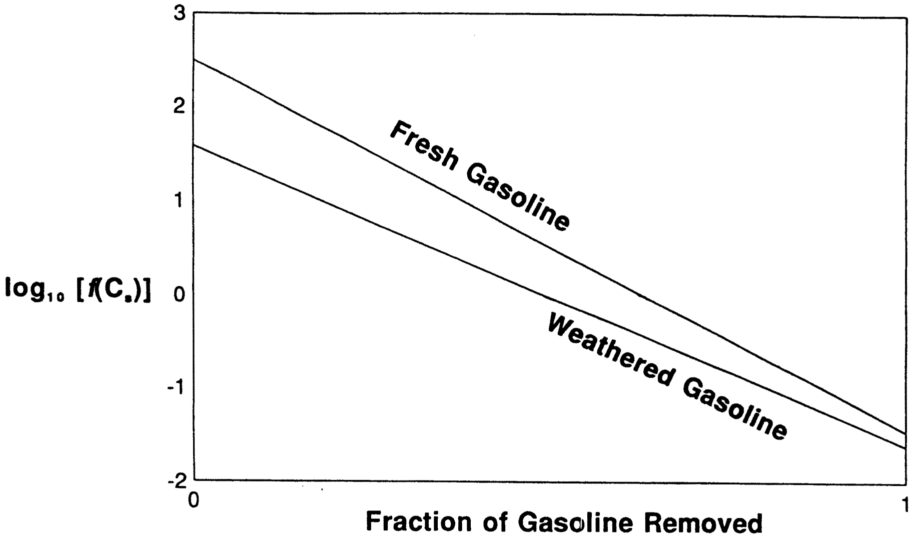

FIGURE 3. $f(C_s)$ for fresh and weathered gasoline. This figure is derived from constituent data in Johnson *et al.* (1990a).

specifies the contaminant, choosing from a list of common volatile soil contaminants or entering a new contaminant with its vapor pressure and vaporization enthalpy. Values for all other parameters are then entered, and the value of the dependent variable is displayed virtually instantaneously.

Of course, the simplifying assumptions that provide this ease of calculation also contribute to the uncertainty in the result. Significant subsurface anisotropies (sewers, foundations, etc.) can upset the assumed radial symmetry of the air flow, and extreme stratification can make the assumption of uniform air flow across the vented stratum inappropriate. However, site data are often inadequate to characterize the anisotropies in any event, and it is rare that horizontal and vertical permeabilities differ by more than an order of magnitude within a vented stratum. Equation 9 can therefore provide reasonable rough estimates of SVE system performance over a wide range of site conditions.

However, because the model assumes the vadose-zone conditions to be uniform with depth, caution should be exercised when applying this model to SVE systems venting strata greater than about 30 ft below grade. In addition, Equation 9 is not appropriate when vertical infiltration of air through the ground surface is virtually nonexistent. Such a situation would arise during venting of a high permeability stratum underlying an extensive, substantial, and continuous stratum of much lower permeability. Fortunately, such situations occur only rarely, and they can be modeled effectively using the sealed surface approach taken by Johnson *et al.* (1990a, 1990b).

V. **EXAMPLES**

Equation 9 indicates that for a fixed cleanup level, changes in vapor extraction rate (Q^o), cleanup time (t), and depth of the vented interval (h) will not effect the effective radius so long as Q^ot/h remains constant. In other words, the same system performance can be obtained in half the time by doubling the vapor-extraction rate or halving the depth of the vented interval.

Figure 4 shows an example of how effective radius varies with Q^ot/h for a variety of common volatile soil contaminants (where cleanup is defined as 90% removal, ideal soil-vapor partitioning and an unsealed surface are assumed). The conditions in this example are typical for SVE systems, and the resulting effective radius varies from a few feet to as much as 70 ft. Effective radius is most sensitive to the volatility of the contaminant; the effective radius for weathered gasoline is 3 to 10 times less than for 1,1,1-trichloroethane under the same conditions. Large changes in Q^ot/h are required to substantially affect effective radius, especially for the more volatile contaminants; doubling the effective radius generally requires increasing Q^ot/h by a factor of 10 to 50.

This relationship between effective radius and Q^ot/h has profound implications regarding SVE system design. Decreasing the spacing between vapor-extraction wells increases the number of wells required, but also decreases the effective radius required. This greatly reduces remediation time and/or soil-gas recovery rate requirements. For example, a reduction in effective radius from 40 ft to 30 ft would

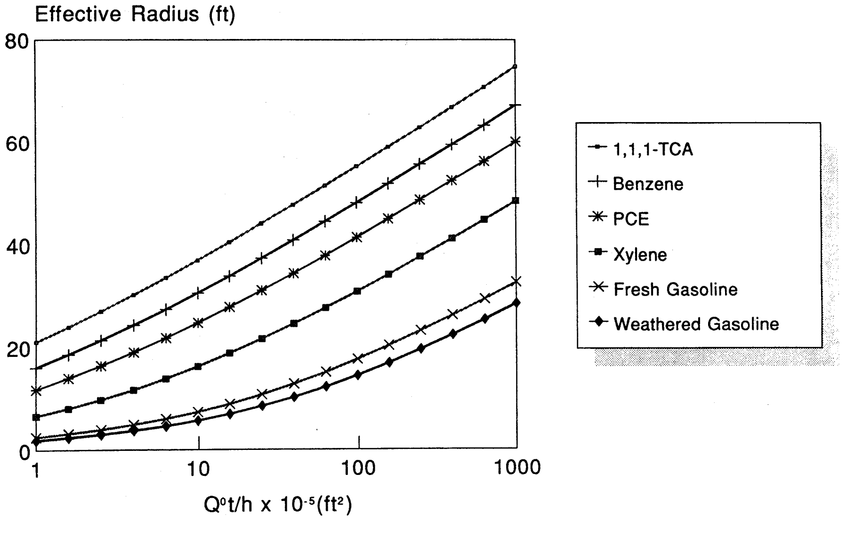

FIGURE 4. Effective radius at a typical SVE site as a function of Q^ot/h for several volatile contaminants (90% cleanup, ideal soil-vapor partitioning, and unsealed surface assumed).

nearly double the number of vapor-extraction wells but would also reduce remediation time by nearly an order of magnitude. The lower soil-gas recovery rates required when effective radius is reduced in many cases results in lower costs associated with less powerful blowers that more than make up for the costs associated with additional vapor-extraction wells.

Effective radius also varies with desired cleanup level, as shown in Figure 5 for a typical unsealed system where Q^o is 30 scfm per vapor extraction well, h is 10 ft, and t is 1 year. Contaminant volatility has a large impact on effective radius, but increasing cleanup level from 90% to 99.99% only decreases the effective radius for single component systems by 35 to 50%. For contaminant mixtures such as gasoline, however, changing cleanup level can have a more dramatic effect. This is because the volatility of the mixture decreases over the course of the SVE process, because the most volatile components are removed first. The volatility of contaminant mixtures is thus a function of cleanup level, and so effective radius is strongly affected by changes in cleanup level.

This model can also be used to assess the effect of soil temperature on effective radius, cleanup level, or remediation time. The effectiveness of SVE can be significantly enhanced by injecting hot air, steam, or radio frequency to heat vadose-zone soil, because $f(C_s)$ increases rapidly with increasing temperature. Evaluating Equation 9 at various temperatures gives an indication of the magnitude of SVE enhancement. For example, 90% removal of fresh gasoline from a 10-ft depth of medium sand, 20 ft from a vapor-extraction well pulling 30 cfm is

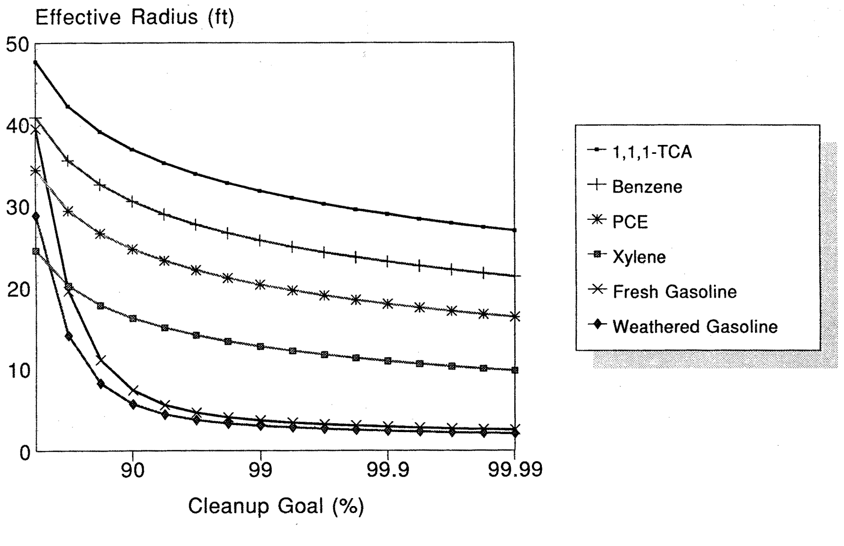

FIGURE 5. Effective radius at a typical SVE site as a function of cleanup goal ($Q^ot/h = 1.6 \times 10^6$ ft^2; ideal soil-vapor partitioning and unsealed surface assumed).

estimated to require almost 5 years of SVE operation at 50°F, but 16 months at 100°F, 6 months at 150°F, and 10 weeks at 200°F.

VI. CONCLUSIONS

A simple one-dimensional model has been developed that can provide rapid order-of-magnitude assessments of potential SVE performance based on very limited data. Because the model uses analytical rather than numerical methods, it has advantages over more sophisticated, multidimensional models, including simplicity, speed, versatility, and robustness. Although accuracy and resolution are somewhat reduced, the use of this model instead of more complicated approaches is generally justified, given the limited site characterization data ordinarily available and the subsurface anisotropies commonly encountered at most small SVE sites. Since 1992, Groundwater Technology, Inc. has been using this model routinely as a design tool for SVE systems.

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