SOIL VAPOR EXTRACTION

1. When to use?

contaminants with vapor pressure greater than 1 mm Hg AND H' > 0.01
the gas conductivity of the soil is 10^-2 to 10^-5 cm/sec (larger better)
(or adequate to allow at least 1 soil gas exchange per day
i.e. permeability > 1 darcy)
biodegradation too slow to effectively use bioventing
large volumes of vadose zone soil contaminated
high soil moisture content has a negative impact on system performance
if gas permeability <0.1 darcy, gas flow will be primarily through fractures or more permeable "lenses" and gas will not more through large areas of the subsurface

[reminder: 1 darcy = 10^8 cm2]

2. Components of SVE system:

Soil Vapor Extraction well(s)
Monitoring wells
Vacuum pumps and/or blowers
Off-Gas Treatment
Optional: air injection well(s), vapor-liquid separator, barrier wells, impermeable cap

Extraction wells:
screened in permeable packing (gravel pack)
well material which is not negatively affected by soil and contaminant properties
(PVC pipe usually adequate; stainless steel in corrosive environments)
screen starts >2-5' below ground surface to prevent short circuiting; the lower range for impermeable ground cover and larger range if open soil
screen penetrates contaminated zone but does not intercept water table
typical diameter of well 2" to 4"
spaced based on radius of influence (Ri)...
Ri depends on vacuum applied, presence of air injection wells, stratigraphy, soil properties, surface soil conditions; typically 30 to 120 ft

Monitoring wells:
around extraction wells to monitor pressure and progress of remediation

Vacuum Pumps
Types:
Liquid Ring
vac 0 - 29 inches Hg, air flows 10 - 100 cfm, frequently used for remediation
Rotor Lobe - similar to liquid ring pump but only used in air perm tests when high vacuum not req'd
Rotary Vance - low maintenance, used for air permeability tests or low volume/moderate vacuum use, maximum vacuum 27" Hg

3. BASIC PRINCIPLES

i) What concentration of contaminant will be in the soil vapor?

Henry's Law: for dilute solutions, the equilibrium partial pressure (P) of the compound can be related to its mole fraction in the aqueous phase (water):
$P = H * x$ when units of H are atm-L/mol, x=mol/L, P = atm

unitless Henry's: H' = Ca/Cw where both concentrations in mg/L

Raoult's Law: for concentrated solutions (such as NAPLs), the equilibrium partial pressure of a compound is related to its pure phase vapor pressure and molar fraction in the NAPL:
P = X * Ppure ; X = mole compound of interest / total moles of compounds in NAPL

Note: vapor phase diffusion is several orders of magnitude faster than liquid phase diffusion. Diffusion controls mass transport under standard conditions.

ii) How will the contaminant partition between the solids, water, and air in the soil?

Sorption: can model as linear isotherm, Freundlich isotherm, or Langmuir isotherm:
a) modeled as linear isotherm
sorbed cmpd / unit sorbent = distribution coeff * equilibrium conc. in water
mg sorbed cmpd/kg soil = Kd * Cw in mg/L
ok for nonpolar organics with soil, in low sorbent loading range, monolayer coverage, low solute concs; bad for high organic content soils
remember that Kd ~ foc Koc
where foc = fraction of organic carbon in soil
Koc = organic carbon:water partition coefficient

b) modeled as Freundlich isotherm
sorbed cmpd / unit sorbent = sorption capacity const * (equil. conc)^(1/n)
mg sorbed cmpd / kg soil = q * Cw^(1/n)
where n = sorption intensity constant

describes multi-layer coverage,....

Recall that at equilibrium: H' = Ca/Cw, so the above solid:water partitioning relationships can be theoretically modified into solid:air partitioning relationships by substituting Ca/H' for Cw.

During SVE at high gas flowrates, diffusion may not be sufficient to maintain "equilibrium" concentrations of the contaminants in the extracted gas.

iii) Why are the equilibrium gas concentrations important?

Optimal removal times (best case scenario) can be estimated by the equilibrium concentrations in the gas (mg contaminant / L air), the air extraction rate (Qa in L/d), and the initial contaminant mass in the soil to be removed (mg contaminant). Only the mass of contaminant within the "radius of influence" of the extraction wells can be removed. Therefore:
Mass contaminant in soil = concentration of contaminant in soil (mg/L) * volume contaminated soil influenced by the air extraction well (L)
M-contam, mg = mg contam/L soil * L soil

Best-case scenario time to remediate = M-contam / (Air flowrate * Contam. conc in air)

4. DESIGN EQUATIONS:

START WITH DARCY'S LAW: Q= K(dh/dl)A
where the head is AIR head and the K is air conductivity.
This applies when slip flow is negligible (not less than 0.8 atm pressure).

$$Ka = \frac{k * pa * g}{\mu air} = \frac{Kw * \mu w * pa}{\mu air * pw}$$

Ka = air conductivity of soil, cm/sec
k = intrinsic permeability of soil (permeability to water via ALL pore space), cm2
pa = density of air, g/cm3
g = gravitational acceleration, 981 cm/s2 at sea level
µair = dynamic viscosity of air, 1.8 E-4 g/cm-s
Kw = hydraulic conductivity of soil, cm/sec
µw = dynamic viscosity of water
pw = density of water, g/cm3

(remember that the density and viscosity of water and air are a function of temperature and atmospheric pressure; these values are available in most Fluid Mechanics books)

When estimating air conductivity from water conductivity, it is assumed that all soil pores are available for air movement (i.e. nearly dry soil). Therefore, this equation usually overestimates Ka

The dynamic or modified field drawdown method of Johnson is the best method for field measurement of k. The procedure:

1. Inject or extract air at a constant rate from a single venting well while measuring the pressure/vacuum changes over time at several monitoring points located in the soil away from the venting well. This method is very similar to methods for measuring the liquid permeability via pump tests.
2. After the data is collected, plot the gage pressure at the monitoring points vs ln time, and solve for the slope of the line at each monitoring location.
3. Solve for k-air (use consistent units for time from the plot with Q)

$$k\text{-}air = Qa * \mu air / [\, 4 * \pi * b * slope]$$

where k-air = the air permeability of the soil (AT the soil moisture content during the field test), cm2
b = screened thickness of the well, cm (if test at the low flowrate so it can be assumed that all airflow in the vadose zone was parallel with the well screen; if a HIGH gas flowrate was used, the thickness of the entire vadose zone should be used for b)
slope = the slope from the linear portion of the data when PRESSURE in g/cm-s2 is plotted versus ln time (note that the units of time used before the natural log is taken do not matter)

Radius of Influence

The radius of influence (Ri) is the maximum distance from the air extraction or injection well where measurable vacuum or pressure (translating to soil gas movement) occurs. Ri depends on the soil properties, configuration of vent well, gas flow rate, soil stratification, etc. It will be larger when the ground surface above the venting area is “impermeable”; i.e. no ‘leakage’ of air into or out of our idealized venting area. In spite of lots of research, Ri still largely empirical or modeled, without a good way to calculate it directly.

If the same in situ gas permeability test used to measure k-air is run long enough to achieve a steady-state level of pressure at a monitoring location, the test data can be used to estimate the radius of influence of the well.

$$k\text{-}air = Qa * \mu air * \ln(Rw/Ri) \;/\; [\, b * \pi * Patm * (1 - (Pw/Patm)^2)\,]$$

where Qa = gas flowrate during test,
µair = air viscosity
Rw = radius of the air injection well
Ri = radius of influence of the air injection well
b = screened interval of the air injection well
Patm = atmospheric pressure
Pw = pressure at the injection well
(be careful to use consistent units; make conversions as needed)

Alternatively, Ri can be estimated for a single, vertical well with no leakage at steady state using the same air permeability test data as:

$$h(r) = \frac{Qa * \ln(Ri/r)}{2 * \pi * T}$$

Qa = air flowrate during test; cm3/sec
r = distance from the extraction well to monitoring well, cm
(may be well radius, rw)
h(r) = steady-state air head drop at r distance from extraction well, cm
(may be head drop in well, h@w)
T = aquifer transmissivity = Ka b = cm2/s

This reduces to: $h(r) = Qa \ln(Ri / r) / [2 \pi Ka\, b]$

Johnson equation to calculate Ri using air permeability test data at steady-state:

$$P(r) = Pw \left[1 + (1 - (Patm/Pw)^2) * \frac{\ln(r/Rw)}{\ln(Rw/Ri)} \right]^{0.5}$$

P(r) = absolute pressure measured at a distance r from the venting well
Patm = absolute ambient pressure
Pw = absolute pressure applied at the vapor extraction well
Rw = air extraction well radius

Note that these methods based on air permeability test data typically underestimate Ri since the tests are usually conducted for less than a day.

Alternatively: $Ri = 1.5 (T * t / S)^{0.5}$ deMarsily, Quantitative Hydrogeology, p. 165
T = transmissivity
S = storativity
t = time test was conducted when T and S calculated

All these estimations assume a single, vertical well without leakage. If there is signficant leakage, the true Ri will be smaller (less drawdown for given location, time).

Moisture and NAPL effects on Air Conductivity

Moisture and NAPL trapped in the pore spaces affects the soil permeability to air. Therefore, equations can correct for varying amounts of pore space not available to gas flow.

$Ka = Ki * Kr$
where Ki = intrinsic gas conductivity of the soil (at residual saturation)
Kr = relative conductivity, a dimensionless ration (0-1) which depends on air saturation
Ka = air conductivity at a given saturation of the soil

Kr = (1 – Se)^2 * [1 – Se ^ (2+λ)/ λ)]
Se = effective saturation = (S – Sr) / (1 – Sr)
Sr = residual saturation (usually 0.03 – 0.2 depending on soil type)
S = total saturation of soil by both water and NAPL,
    = (vol water + vol NAPL) / total pore volume = 0 – 1
λ = pore size distribution parameter (usually 2 to 4)

Real-World Design

System Design - software packages available to help
    HyperVentilate, Shell Oil Company, 1991. P.C. Johnson.

Horizontal air extraction wells are becoming popular. These work well in cases with large area of contamination with “long” geometry and/or shallow water table. Up to 180’ of “screened interval” can be achieved. Used to extract gas under buildings, parking lots, etc.

5. COSTS

Vertical well SVE:
$10 to $50 per ton; small sites may cost as much as $150/ton
    more cost efficient when vadose zone >10 ft deep

Horizontal wells for SVE:
    well installation around $40/ft (depending on depth and soil type)

REFERENCES:

UConn/EPA Course. F- Soil Vapor Extraction
Suthersan. 1997. Remediation Engineering Design Concepts. CRC Press.