LECTURE 11

SVE & AIR SPARGING DESIGN,
PERMEABLE REACTIVE BARRIERS
Soil Vapor Extraction


Vapor transport in the subsurface

\[ q_a = \frac{k_a}{\mu_a} \nabla P_a \]

- \( q_a \) = airflow per unit area \([L/T]\) (specific discharge)
- \( k_a \) = apparent permeability of soil \([L^2]\)
- \( \mu_a \) = air viscosity \([M/L/T]\) = \(1.8 \times 10^{-4} \) g/cm-s = 0.018 cP
- \( \nabla P_a \) = pressure gradient \([M/L^2/T^2]/L] = [M/L^2/T^2]\)
- \( \rho_a \) = density of air \([M/L^3]\) \(\approx 0.0012 \) g/cm\(^3\)
- \( g \) = gravitational acceleration \([L/T^2]\)
Vapor transport equation is simply Darcy’s Law:

\[ Q_a = q_a A = \frac{k_a}{\mu_a} \nabla P_a A = \frac{k_a \rho_a g}{\mu_a} \left( \frac{\nabla P_a}{\rho_a g} \right) A = K_i A \]

Units:

\[ = \left( \frac{L^2}{M/L^3} \right) \left( \frac{L}{T^2} \right) \left( \frac{M}{L^2 T^2} \right) L^2 = \left( \frac{L}{T} \right) \left( \frac{L}{L} \right) L^2 \]
Apparent permeability of soil is closely related to intrinsic permeability but somewhat greater.

Porosity is decreased by moisture in soil.

Gas slippage (non-zero velocity at solid surfaces) increases transport.

Intrinsic permeability approximates apparent permeability in absence of site-specific data.
Gas pressure

**Absolute pressure** is measured relative to an absolute pressure of zero
- Atmospheric pressure = \(14.7 \text{ psia} = 1 \text{ atmosphere}\)
- psi = pounds (force) per square inch
- Absolute pressure cannot be negative

**Gauge pressure** is measured relative to atmospheric pressure
- Define atmospheric pressure as zero = \(0 \text{ psig}\)
- Gauge pressure can be negative

\[ P_{\text{gauge}} = P_{\text{abs}} - 14.7 \quad \text{(in psi units)} \]
Units for gas calculations

Volumetric air flow

Equipment is based on standard conditions—need to convert to actual conditions for design

\[
\text{ACFM} = \text{SCFM} \times \frac{1\text{ atm}}{\text{actual pressure}} \times \frac{460 + \text{actual temp}}{460 + \text{standard temp}}
\]

CFM = cubic feet per minute
SCFM = standard cubic feet per minute
ACFM = actual cubic feet per minute
Units for gas calculations

Concentration

Concentration is measured and reported in ppmv (parts per million by volume)

Convert to mass per volume with:

\[
mg/L = \frac{P \text{ in atm} \times MW}{1000 \times 0.0821 \times (T + 273)} \text{ ppmv}
\]
SVE design process

Test applicability

Rough estimate
- Estimate vapor concentration
- Estimate removal rate and time

Design
- Field permeability testing

Refined estimate
- Estimate removal rate and time
- Estimate vapor flow rate
SVE Applicability Nomograph

Vapor Pressure (mm Hg)

- Butane
- Pentane
- Benzene
- Toluene
- Xylene
- Phenol
- Naphthalene
- Aldicarb

Soil Air Permeability

- Success Very Likely
- Success Somewhat Likely
- Success Less Likely

SVE Likelihood of Success

Match Point

Time Since Release

- Weeks
- Months
- Years

- High (Gravel, Coarse Sand)
- Medium (Fine Sand)
- Low (Clay)

Determine applicability of SVE

Applicability of SVE depends on contaminants and porous medium

Use design nomograph:
  - Select appropriate soil permeability
  - Within that soil permeability, enter on right at “time since release”
  - Move horizontally to “soil air permeability”
  - Draw straight line to “contaminant/vapor pressure”
  - Where line crosses “SVE likelihood of success” gives first estimate of success
SVE Applicability Nomograph

Vapor Pressure (mm Hg)

- Butane
- Pentane
- Benzene
- Toluene
- Xylene
- Phenol
- Naphthalene
- Aldicarb

10^4, 10^3, 10^2, 10^1, 1, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}

Soil Air Permeability

- Success Very Likely
- Success Somewhat Likely
- Success Less Likely

Match Point

SVE Likelihood of Success

- High (Gravel, Coarse Sand)
- Medium (Fine Sand)
- Low (Clay)

Time Since Release

Determine applicability of SVE

Other considerations not in nomograph:
- SVE is less effective in moist soil
- SVE is less effective in high organic content soil
“Practical method” for SVE design

Next step after determining SVE is applicable

Reference (widely cited):

Estimate vapor concentration in soil

\[ C_{est} = \sum_i x_i P_i^v M_{w,i} \frac{RT}{RT} \]

- \( C_{est} = \) estimated vapor concentration [mg/L]
- \( x_i = \) mole fraction of component \( i \) in NAPL (e.g., benzene in gasoline [dimensionless])
- \( P_i^v = \) pure component vapor pressure at temperature \( T \) [atm]
- \( M_{w,i} = \) molecular weight of component \( i \) [mg/mole]
- \( R = \) gas constant [L-atm/mole/°K]
- \( T = \) absolute temperature of NAPL [°K]

For “fresh” gasoline, \( C_{est} \approx 1300 \) mg/L
For “weathered” gasoline, \( C_{est} \approx 220 \) mg/L
Estimate removal rate and removal time

\[ R_{\text{est}} = C_{\text{est}} \cdot Q \]

- \( R_{\text{est}} \) = estimated removal rate
- \( Q \) = estimated extraction flow rate
  - = 10 to 100 scfm generally
  - = 100 to 1000 scfm in large installations or very sandy soil

\[ \tau = M_{\text{spill}} / R_{\text{est}} \]

- \( \tau \) = estimated removal time
- \( M_{\text{spill}} \) = estimated mass of spill
Refine estimate of vapor flow rate

First, estimate air permeability from aquifer hydraulic conductivity:

$$k_a \approx k = \frac{\mu_w}{\rho_w g} K$$

$k = \text{intrinsic permeability [cm}^2\text{]}$

$K = \text{hydraulic conductivity [cm/s]}$

$\mu_w = \text{dynamic viscosity of water} \approx 1.0 \text{ cP} = 0.01 \text{ g/cm/s}$

$\rho_w = \text{density of water} \approx 1.0 \text{ g/cm}^3$

Note: vadose soil may not be same as aquifer soil
Refine estimate of vapor flow rate

Next, estimate flow rate to vapor extraction well:

\[
\frac{Q}{H} = \pi \frac{k_a}{\mu_a} P_{\text{well}} \left[ 1 - \left( \frac{P_{\text{atm}}}{P_{\text{well}}} \right)^2 \right] \frac{\ln(R_{\text{well}} / R_I)}{\ln(R_{\text{well}} / R_I)}
\]

H = screen length of extraction well [L]

\( P_{\text{atm}} \) = atmospheric pressure = 1 atm

\( P_{\text{well}} \) = absolute pressure at extraction well [atm]

\( \approx 0.9 \) to 0.95 atm (typical values)

\( R_{\text{well}} \) = well radius [L]

\( = 2 \) or 4 inches = 5 or 10 cm typically

\( R_I \) = extraction well radius of influence [L]

\( \approx 40 \) feet \( \approx 12 \) m (Note: result is not very sensitive to \( R_I \))
Revise removal rate and removal time

\[ R_{est} = (1-\phi) \, C_{est} \, Q \]
\[ \phi = \text{estimated fraction of flow through uncontaminated soil} \]
(see Johnson et al., 1999 for refinements)

\[ \tau = \frac{M_{spill}}{R_{est}} \]

SVE for mixtures

Vapor concentration \( (C_{\text{est}}) \) is function of chemical vapor pressure

VOCs with highest vapor pressure are removed first

Mixture “weathers” during SVE—becoming progressively less volatile and heavier
Air permeability testing

Principles are the same as conducting aquifer tests (pump tests) for water flow

Procedure:

- Install vapor extraction well and vapor pressure observation wells
- Extract vapor from extraction well (measuring air flow Q)
- Monitor pressure vs. time at observation wells
- Fit pressure vs. time curves to type curves
- Monitor atmospheric pressure during test
Type curves for permeability tests

Theis equation for transient pressure response:

\[ P' = \frac{Q}{4\pi b \left( k_a / \mu_a \right)} W(u) \]

\( P' = \) “gauge” pressure measured at distance \( r \) and time \( t \)
\( b = \) vadose zone (or stratum) thickness

\( W(u) = \) well function

\[ W(u) = \int_u^\infty \frac{e^{-x}}{x} \, dx \]
Type curves for permeability tests

Theis equation (continued)

\[ u = \frac{r^2 \varepsilon \mu_a}{4k_a P_{atm} t} \]

\( \varepsilon = \) air-filled porosity [fraction]
\( r = \) distance to observation well [L]
\( t = \) time since start of extraction [T]
Type curves for permeability tests

Jacob approximation for \( u < 0.01 \):

\[
P' \approx \frac{Q}{4\pi b(k_a / \mu_a)} \left( -0.5772 - \ln \left( \frac{r^2 \varepsilon \mu_a}{4k_a P_{atm} t} \right) \right)
\]

or:

\[
P' = \frac{Q}{4\pi b(k_a / \mu_a)} \log \left( \frac{2.25k_a P_{atm} t}{r^2 \varepsilon \mu_a} \right)
\]
Another useful form of Jacob approximation:

\[
P' \approx \frac{Q}{4\pi b \left( k_a / \mu_a \right)} \left( -0.5772 - \ln \left( \frac{r^2 \varepsilon \mu_a}{4k_a P_{atm}} \right) + \ln(t) \right)
\]

\( P' \) is proportional to \( \ln(t) \) and will plot as a straight line on semi-log paper.
Interpreting Jacob Type Curve

Slope and intercept allow determination of $k_a$:

Slope:

$$B = \frac{Q}{4\pi b(k_a / \mu_a)}$$

$Q$ and $\mu_a$ are known, $b$ can be estimated $\rightarrow k_a$

Intercept:

$$A = \frac{Q}{4\pi b(k_a / \mu_a)} \left( -0.5772 - \ln \left( \frac{r^2 \varepsilon \mu_a}{4k_a P_{atm}} \right) \right)$$

Solve for $\varepsilon$
Type curve with leakage

Air coming from surface is “leakage” and can be accounted for

Solution for “leaky” system:

\[ P' = \frac{Q}{4\pi b \left(\frac{k_a}{\mu_a}\right)} W(u, r/B) \]

\( W(u, r/B) = \) leaky well function

\( B = \) leakage factor [L]
Leakage effects in aquifer response

Determine radius of influence

Two possible procedures from pump-test data:

1. Plot $P'$ vs. distance from the pumping well
   Radius of influence = distance at which:
   $P' = 0.01$ to $0.1 \ P'_w$
Determine radius of influence

Two possible procedures from pump-test data:

2. Find $R_I$ from equation for steady-state vapor flow:

$$P(r) = P_{\text{well}} \sqrt{1 + \left(1 - \left(\frac{P_{\text{atm}}}{P_{\text{well}}}\right)^2\right) \frac{\ln(r/R_{\text{well}})}{\ln(R_{\text{well}}/R_I)}}$$

Assumes $P = P_{\text{atm}}$ at $r = R_I$, $P = P_{\text{well}}$ at $r = R_{\text{well}}$
Design of SVE systems

Use $R_i$ to ensure overlap of individual SVE wells:
Design consideration for SVE

Soil vacuum causes water table to rise, reducing thickness of unsaturated zone

If water table is shallow, water vapor entrained into SVE system can be a problem, especially due to system freezing in winter

Surface cap is needed to reduce entrainment of clean air from the atmosphere

Cap can lead to anaerobic conditions in vadose zone
Can cause chlorinated solvent degradation and methane accumulation (explosion hazard)
Air inlets can be provided to prevent stagnant zones, anaerobic conditions
SVE design

EPA computer program to assist in SVE design – HyperVentilate:

Variations on SVE

Bioventing – stimulation of biodegradation by introducing air and possibly nutrient supplements into vadose zone
  Air flow rate is managed to optimize biodegradation, not vapor extraction

Hot air or steam injection – enhances volatility

Horizontal wells – can be more efficient than conventional wells
Air sparging
Design considerations for air sparging

Pilot test is critical – needed to determine $R_i$, which is the key design parameter

Measurements during pilot test should include:
- Ground-water elevation
- Dissolved oxygen and contaminant concentration in saturated zone
- Vapor pressure, vapor concentration in vadose zone
Pilot tests for air sparging

Water level rise is transient – dissipates after start-up period and is poor indicator of $R_I$

DO is a key measure to estimate $R_I$

Contaminant concentration is expensive to measure
Design considerations for air sparging

Despite importance of $R_l$ as a design parameter, it is difficult to measure and should be used conservatively.

- Short-circuiting in soil channels in high-K soils and bypassing low-K zones can reduce effectiveness within radius of influence.

- Air sparging is less effective in high-K and low-K soils due to these effects.
Design considerations for air sparging

Sparging reduces hydraulic conductivity since air can fill significant percentage of void space

Air bubbles tend to form in grain sizes larger than 2 mm (coarse sand) – formation is a function of the Bond Number


Air sparging can stimulate aerobic biodegradation

Biofouling of air sparge wells can be an issue
Variations on air sparging

Trench sparging – excavated trench, backfilled with crushed stone and equipped with sparging pipes

Horizontal wells

Pulsed sparging – pulsing of air flow sometimes increases effectiveness

Biosparging - stimulation of biodegradation by introducing air and possibly nutrient supplements
Permeable reactive barrier

Sometimes called “treatment wall” or “reactive wall”

Wall of material installed in the subsurface that causes a desired reaction

“Barrier” is made permeable to encourage contaminants to travel through the reactive material
Zero-valence iron wall

Original and most common type of reactive wall

Iron walls cause dechlorination of chlorinated organic solvents

Discovered “by accident” during testing of effect of well materials on measured concentrations

Exact mechanism unknown
Zero-valence iron wall

Oxygenated ground water enters the wall and causes the iron to oxidize:

\[ 2 \text{Fe}^0 + \text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{Fe}^{2+} + 4 \text{OH}^- \]

Reaction usually depletes all oxygen within short distance into the wall
Depletion of oxygen leads to dechlorination of organic solvents:

\[ 3\text{Fe}^0 \rightarrow 3\text{Fe}^{2+} + 6\text{e}^- \]

\[ \text{C}_2\text{HCl}_3 + 3\text{H}^+ + 6\text{e}^- \rightarrow \text{C}_2\text{H}_4 + 3\text{Cl}^- \]

End products are chloride and ethane.
Other chemical reaction pathways probably occur

Ferric hydroxide (Fe(OH)$_3$) or ferric oxyhydroxide (FeOOH) may precipitate in wall and reduce K
Other materials for treatment walls for chlorinated solvents

Iron and palladium
Iron and nickel
Other metals

None are as cost effective as iron

Materials must be oil-free
   Iron from metals cuttings with oil do not work
Design of treatment walls

Reaction is presumed to follow first-order reaction:

\[
\frac{C(t)}{C_0} = e^{-kt}
\]

Reaction coefficient is determined in the lab by column tests.
Column Test

Column has intermediate sampling points to extract water at different travel times as it passes through iron
Analysis of column-test results

Analyze column-test results to find $k$:

$$
\ln \left( \frac{C}{C_0} \right) = -kt
$$

Reaction half-life, $t_{1/2} = 0.69 / k$
Design of treatment walls

Determine desired residence time, $\tau$, in reactive wall based on desired $C_{\text{end}}$, known $C_0$

$$\tau = -\frac{1}{k} \ln \left( \frac{C_{\text{end}}}{C_0} \right) = -\frac{t_{1/2}}{0.69} \ln \left( \frac{C_{\text{end}}}{C_0} \right)$$

Compute necessary wall thickness as: $b = u\tau$

where $u = Ki/n$

$K/n$ is available from column tests with non-reactive tracers
Design curves for PRB

Example:
\[ t_{\frac{1}{2}} = 1 \text{ hr} \]
\[ u = 2 \text{ ft/day} \]

Wall thickness = 1 foot

PRB Effectiveness Over Time

Treatment wall design alternatives

Funnel and gate includes flow barriers (slurry wall or sheet pile) to direct flow to smaller PRB

Trench and gate for low permeability formations


Installation can include deep soil mixing, slurry technologies (including “biopolymers”), or removable modules of treatment media
Funnel and Gate System

Permeable Reactive Barrier Installation

Bio-Polymer Installation of PRB

**Alternative PRB treatment media**

Wood chips – nitrate removal  

Iron – chromium VI reduction to Cr(III)  

Zeolites – heavy metals (Pb, Cr, As, Cd)  

Iron slag – phosphorus
Source: Los Alamos National Laboratory (see notes).

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Multi-media PRB at Los Alamos, NM

Installed across canyon downstream of wastewater discharge from Radioactive Liquid Waste Treatment Facility

Designed to treat:
- strontium-90; americium-241; uranium;
- plutonium-238, -239 and -240;
- perchlorate; nitrate;
- heavy metals
Downstream view of multi-media PRB
Side view of multi-media PRB
PRB installation cost = $0.9 million

Crews install a Permeable Reactive Barrier in Mortandad Canyon. The barrier will help control legacy contamination in the canyon by scrubbing shallow groundwater as it moves downstream.

Permeable reactive barriers

For more information:

PRBs are an area of active research reported in technical journals.
Soil Flushing

Uses water (usually with additives) to physically displace contaminants

Possible additives:

- **Co-solvents**
  - Hydrophilic organic solvents (usually alcohols) displace and dissolve hydrophobic organic contaminants

- **Surfactants**
  - NAPL mobilization by reducing interfacial tension

- **Alkali**
  - Creates surfactants in-situ
Soil Flushing