LECTURE 11

SVE & AIR SPARGING DESIGN, PERMEABLE REACTIVE BARRIERS

Soil Vapor Extraction

See image at the Web site of Wayne Perry, Inc., Soil Vapor Extraction Systems, http://www.wpinc.com/remedy/remedy30.html Accessed May 11, 2004.

SVE Design

Vapor transport in the subsurface

$$q_a = \frac{k_a}{\mu_a} \nabla P_a$$

q_a = airflow <u>per unit area</u> [L/T] (specific discharge)

k_a = apparent permeability of soil [L^2]

μ_a = air viscosity [M/L/T] = 1.8 x 10^{-4} g/cm-s = 0.018 cP

∇P_a = pressure gradient [(M/L/T^2)/L] = [M/L^2/T^2]

ρ_a = density of air [M/L^3] $\cong$ 0.0012 g/cm^3

g = gravitational acceleration [L/T^2]

SVE Design

Vapor transport equation is simply Darcy's Law:

$$Q_a = q_a A = \frac{k_a}{\mu_a} \nabla P_a A = \frac{k_a \rho_a g}{\mu_a} \left(\frac{\nabla P_a}{\rho_a g} \right) A = KiA$$

Units:

$$= \frac{\left(L^2\right)\left(\dfrac{M}{L^3}\right)\left(\dfrac{L}{T^2}\right)}{\left(\dfrac{M}{LT}\right)} \left(\frac{\left(\dfrac{M}{L^2 T^2}\right)}{\left(\dfrac{M}{L^3}\right)\left(\dfrac{L}{T^2}\right)} \right) L^2 = \left(\frac{L}{T}\right)\left(\frac{L}{L}\right) L^2$$

Apparent permeability

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 psia = 1 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 psig
>
> Gauge pressure can be negative

$P_{gauge} = P_{abs} - 14.7$ (in psi units)

Units for gas calculations

Volumetric air flow

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

$$\mathrm{ACFM} = \mathrm{SCFM} \times \frac{1\,\mathrm{atm}}{\text{actual pressure}} \times \frac{460 + \text{actual temp}}{460 + \text{standard temp}}$$

CFM = cubic feet per minute
SCFM = standard cubic feet per minute
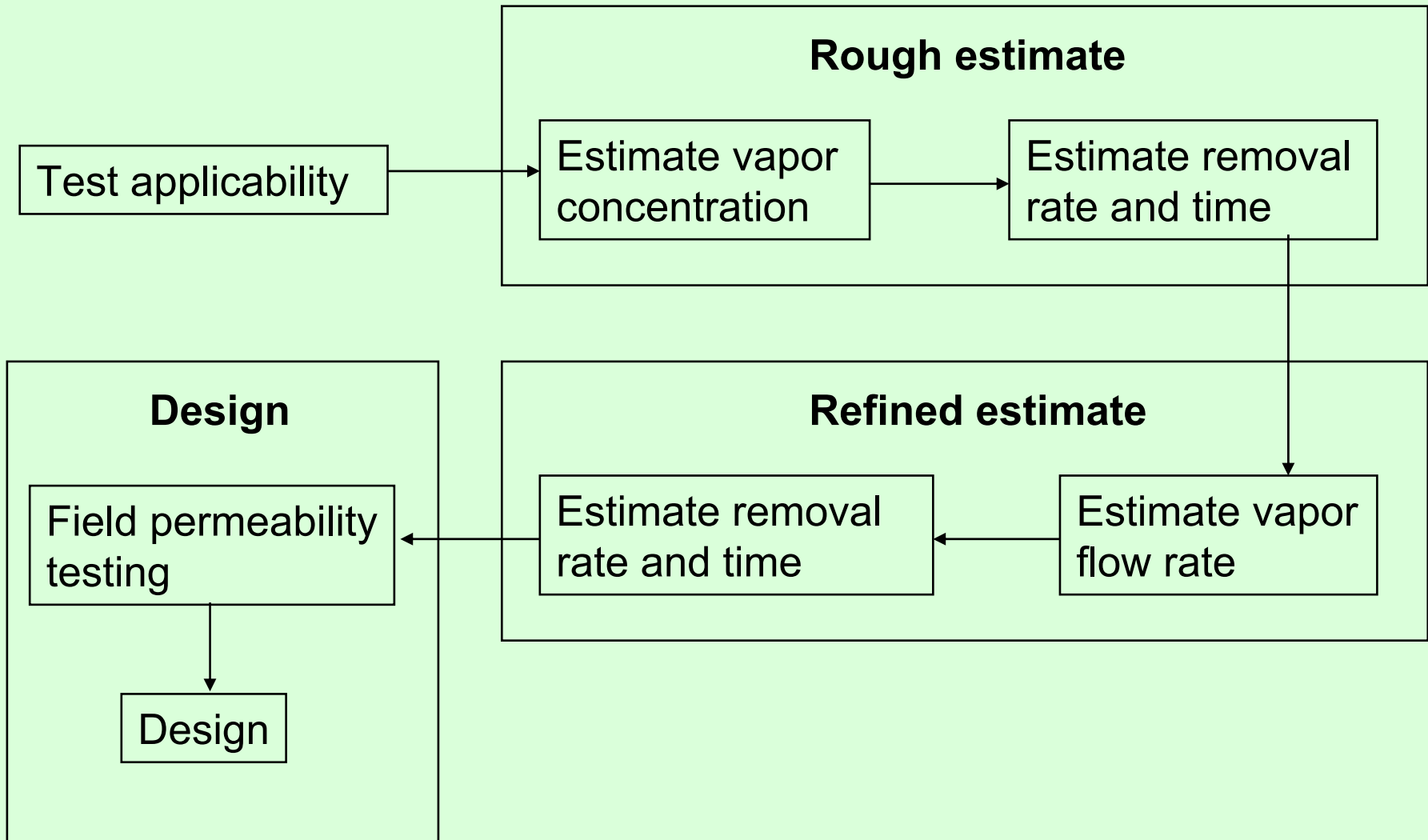ACFM = actual cubic feet per minute

Units for gas calculations

Concentration

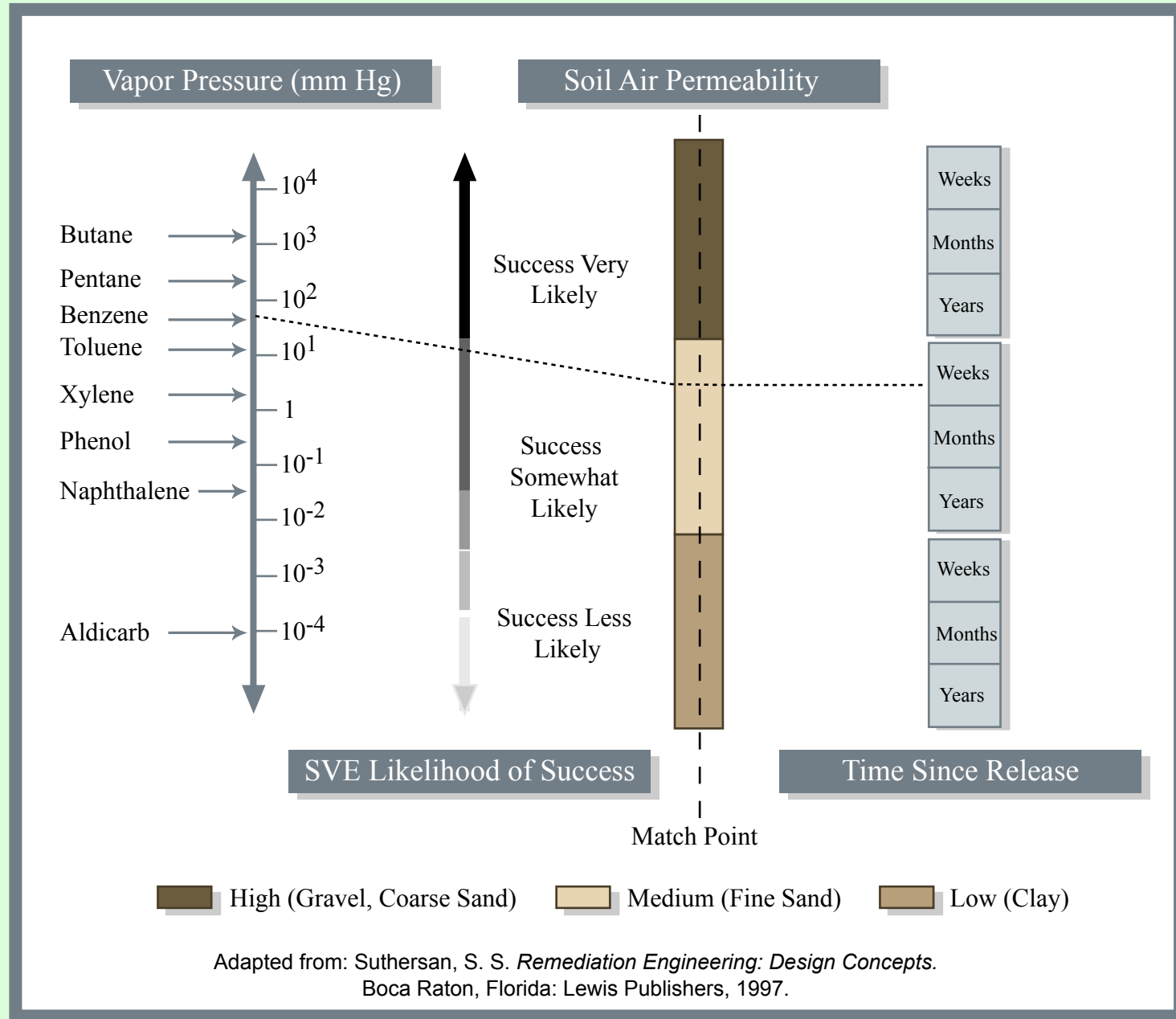Concentration is measured and reported in ppmv (parts per million by volume)

Convert to mass per volume with:

$$\text{mg/L} = \frac{\text{P in atm} \times \text{MW}}{1000 \times 0.0821 \times (\text{T} + 273)}\text{ppmv}$$

SVE design process

Rough estimate

Test applicability → Estimate vapor concentration → Estimate removal rate and time

Refined estimate

Estimate removal rate and time ← Estimate vapor flow rate

Design

Field permeability testing → Design

SVE Applicability Nomograph

Vapor Pressure (mm Hg)

- Butane → 10^3
- Pentane → 10^2
- Benzene → 10^2
- Toluene → 10^1
- Xylene → 1
- Phenol → 10^{-1}
- Naphthalene →
- Aldicarb → 10^{-4}

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

SVE Likelihood of Success

Time Since Release

Weeks, Months, Years

Weeks, Months, Years

Weeks, Months, Years

Match Point

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

Adapted from: Suthersan, S. S. *Remediation Engineering: Design Concepts.*
Boca Raton, Florida: Lewis Publishers, 1997.

Determine applicability of SVE

Applicability of SVE depends on contaminants and porous medium

Use design nomograph:

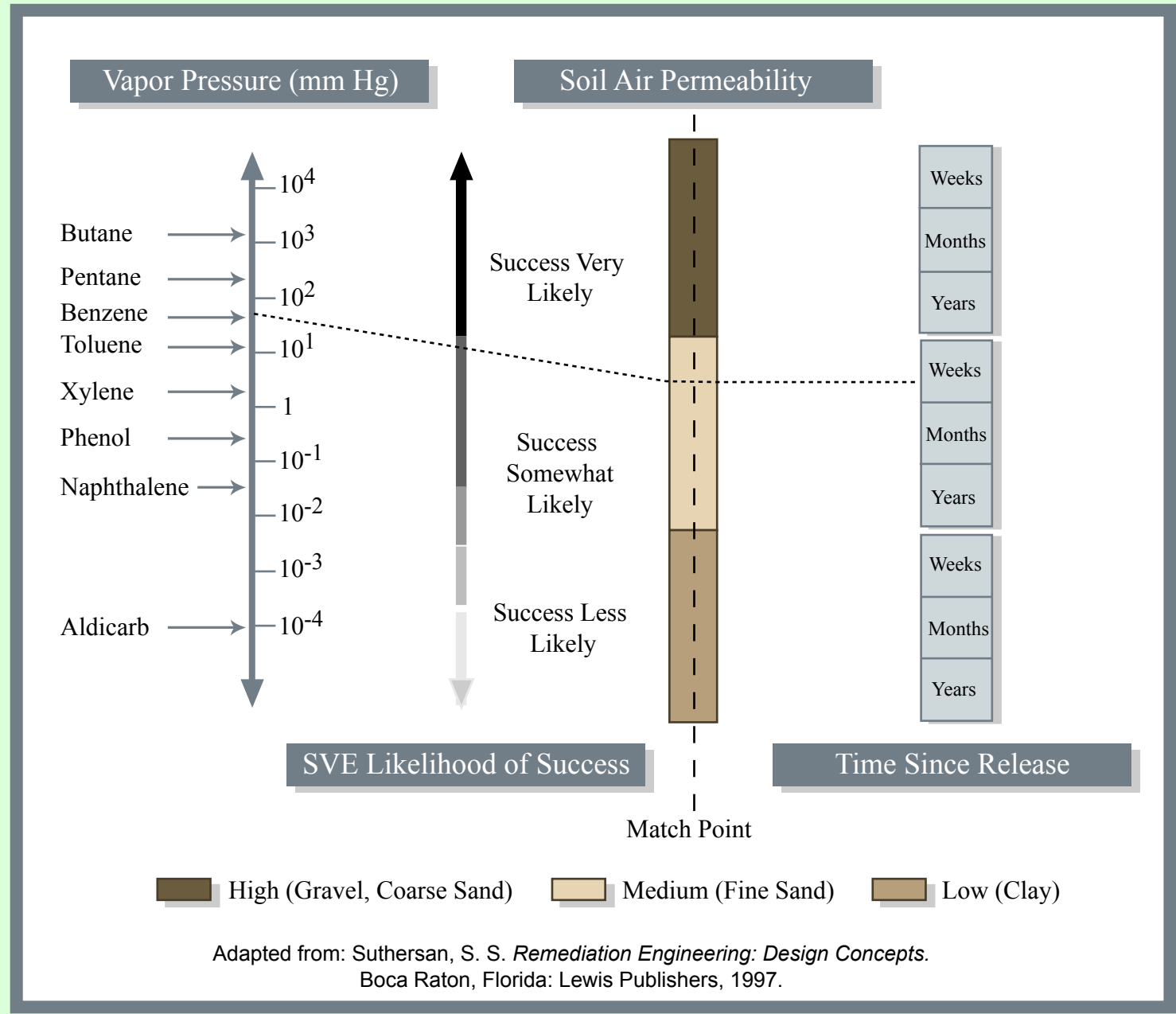- Select appropriate soil permeability
- Within that soil permeability, enter on right at "time since release"
- Move horizontally to "soil air permeability"
- Draw straight line to "contaminant/vapor pressure"
- Where line crosses "SVE likelihood of success" gives first estimate of success

SVE Applicability Nomograph

Vapor Pressure (mm Hg)

Soil Air Permeability

Butane → 10^3
Pentane → 10^2
Benzene →
Toluene → 10^1
Xylene → 1
Phenol → 10^{-1}
Naphthalene →
10^{-2}
10^{-3}
Aldicarb → 10^{-4}

10^4

Success Very Likely

Success Somewhat Likely

Success Less Likely

Weeks
Months
Years

Weeks
Months
Years

Weeks
Months
Years

SVE Likelihood of Success

Time Since Release

Match Point

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

Adapted from: Suthersan, S. S. *Remediation Engineering: Design Concepts.*
Boca Raton, Florida: Lewis Publishers, 1997.

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):

P.C. Johnson, C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart, 1990. A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil-Venting Systems. *Ground Water Monitoring Review*, Vol. 10, No. 2, Pp. 159-178. Spring 1990.

Estimate vapor concentration in soil

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

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/ºK]

T = absolute temperature of NAPL [ºK]

For "fresh" gasoline, $C_{est} \cong 1300$ mg/L

For "weathered" gasoline, $C_{est} \cong 220$ mg/L

Estimate removal rate and removal time

$$R_{est} = C_{est} \, Q$$

R_{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

$$\tau = M_{spill} / R_{est}$$

τ = estimated removal time

M_{spill} = estimated mass of spill

Refine estimate of vapor flow rate

First, estimate air permeability from aquifer hydraulic conductivity:

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

k = intrinsic permeability [cm^2]

K = hydraulic conductivity [cm/s]

μ_w = dynamic viscosity of water $\cong$ 1.0 cP = 0.01 g/cm/s

ρ_w = density of water $\cong$ 1.0 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:

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

H = screen length of extraction well [L]

P_{atm} = atmospheric pressure = 1 atm

P_{well} = <u>absolute</u> pressure at extraction well [atm]
$\cong$ 0.9 to 0.95 atm (typical values)

R_{well} = well radius [L]
= 2 or 4 inches = 5 or 10 cm typically

R_I = extraction well radius of influence [L]
$\cong$ 40 feet $\cong$ 12 m (Note: result is not very sensitive to R_I)

Revise removal rate and removal time

$R_{est} = (1-\phi)\, C_{est}\, Q$

ϕ = estimated fraction of flow through uncontaminated soil

(see Johnson *et al.*, 1999 for refinements)

$\tau = M_{spill} / R_{est}$

P.C. Johnson, C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart, 1990. A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil-Venting Systems. *Ground Water Monitoring Review*, Vol. 10, No. 2, Pp. 159-178. Spring 1990.

SVE for mixtures

Vapor concentration (C_{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)

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

ε = 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:

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

or:

$$P' = \frac{Q}{4\pi b(k_a / \mu_a)} \log\left(\frac{2.25 k_a P_{atm} t}{r^2 \varepsilon \mu_a} \right)$$

Type curves for permeability tests

Another useful form of Jacob approximation:

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

P' is proportional to ln(t) and will plot as a straight line on semi-log paper

Jacob Type Curve

See Figure 9.13 in: Driscoll, F. G., 1986. Groundwater and wells. Johnson Division, St. Paul, Minnesota.

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 μ_a are known, b can be estimated $\rightarrow k_a$

Intercept:

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

Solve for ε

Type curve with leakage

Air coming from surface is "leakage" and can be accounted for

Solution for "leaky" system:

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

W(u, r/B) = leaky well function
B = leakage factor [L]

Leakage effects in aquifer response

See Figure 9.19 in: Driscoll, F. G., 1986. Groundwater and wells. Johnson Division, St. Paul, Minnesota.

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:

   $$P' = 0.01 \text{ to } 0.1 \ P'_w$$

Determine radius of influence

Two possible procedures from pump-test data:

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

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

Assumes $P = P_{atm}$ at $r = R_I$, $P = P_{well}$ at $r = R_{well}$

Design of SVE systems

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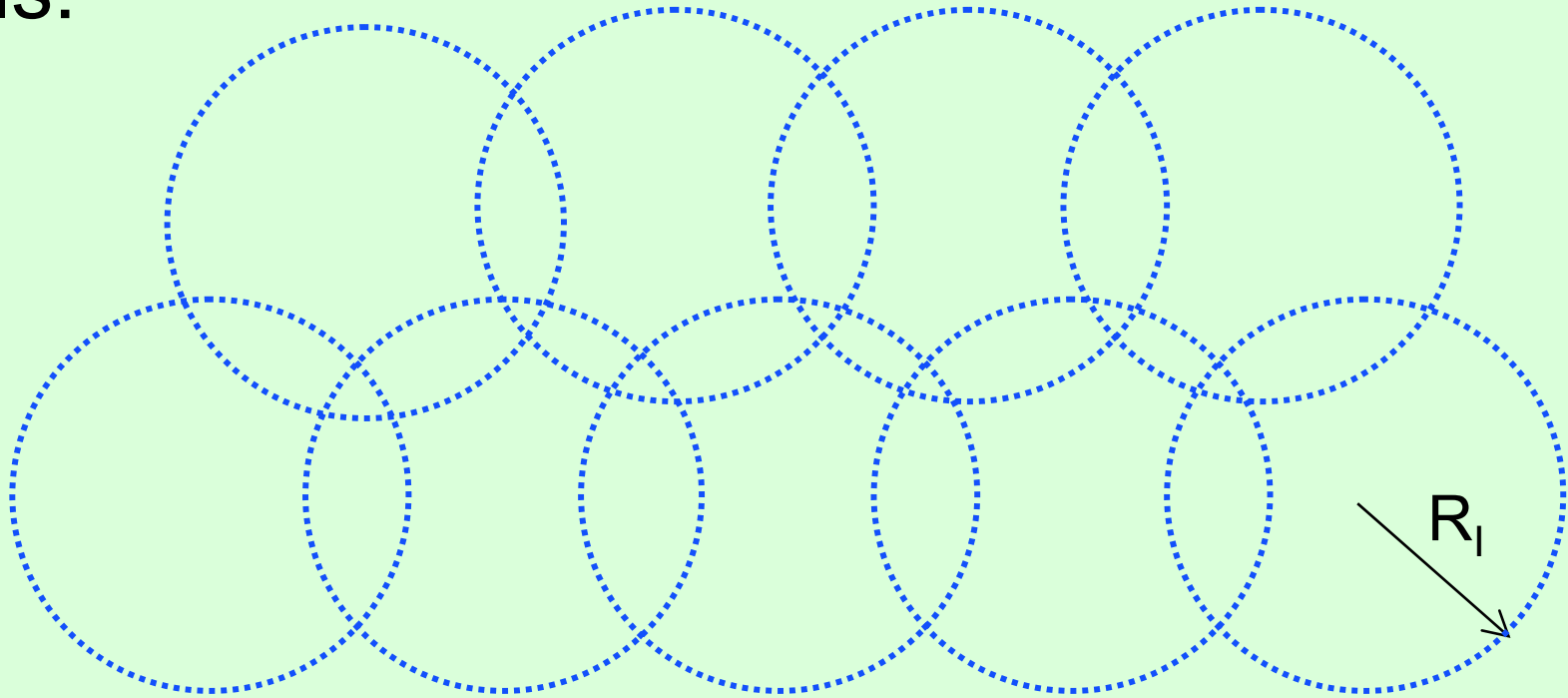
Design consideration for SVE

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:

Kruger, C. A. and J. G. Morse, 1993. Decision-support software for soil vapor extraction technology application: HyperVentilate. Report Number EPA/600/R-93/028. Risk Reduction Engineering Laboratory, U.S. EPA, Cincinnati, OH.

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
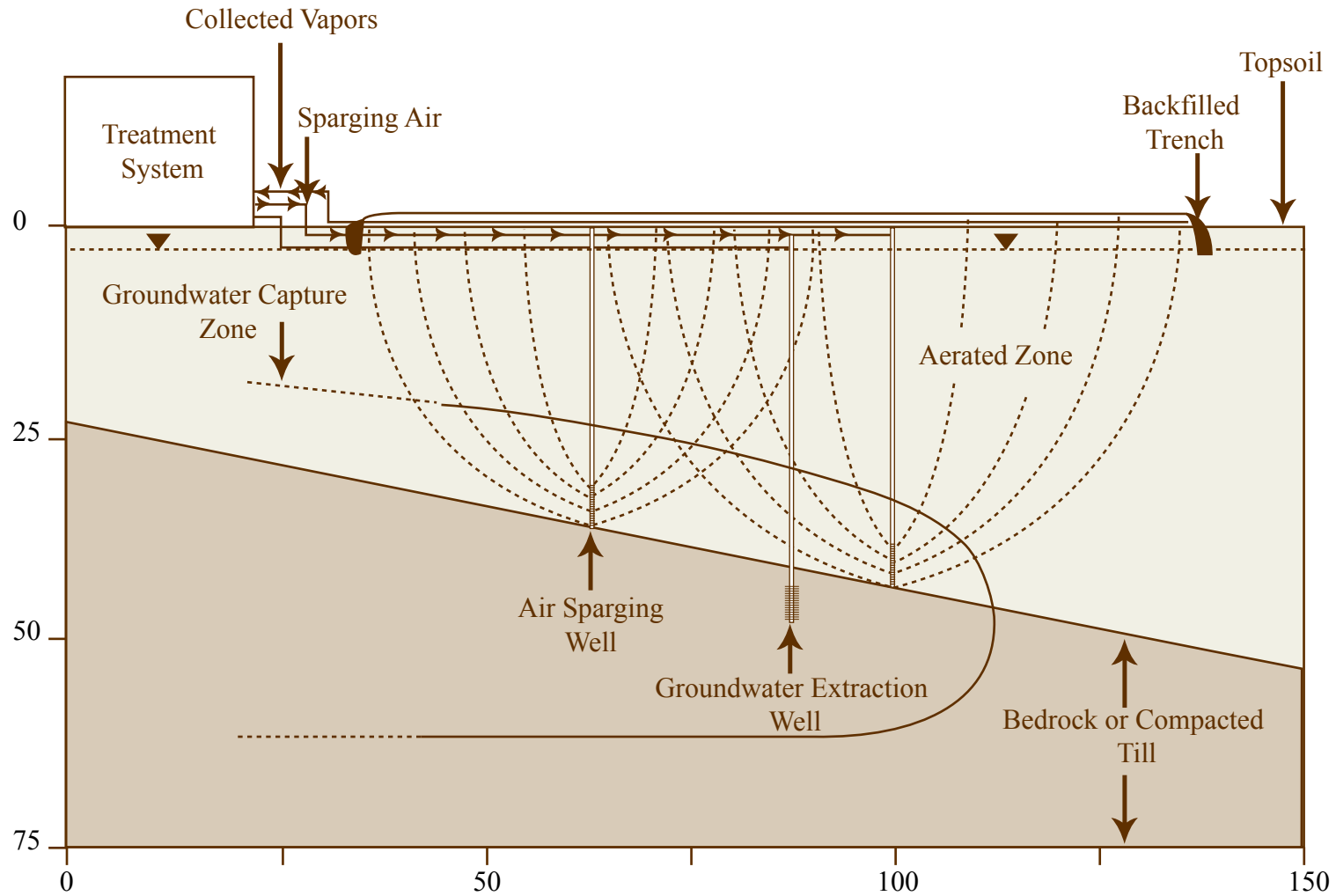
Design considerations for air sparging

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_I 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

Brooks, M. C., W. R. Wise and M. D. Annable, 1999. "Fundamental Changes in In Situ Air Sparging Flow Patterns." *Ground Water Monitoring and Remediation*, Vol. 19, No. 2, Pp. 105.

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:

$$2\,Fe^0 + O_2 + 2\,H_2O \rightarrow 2\,Fe^{2+} + 4\,OH^-$$
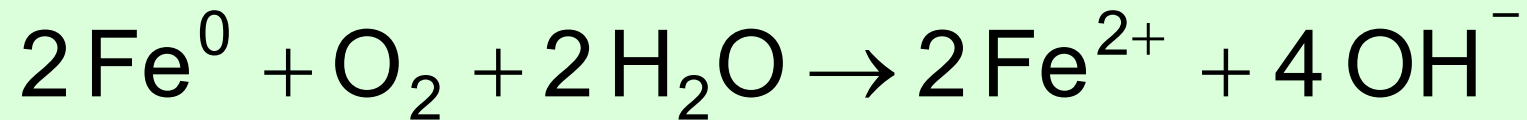
Reaction usually depletes all oxygen within short distance into the wall

Zero-valence iron wall

Depletion of oxygen leads to dechlorination of organic solvents:

$$3Fe^0 \rightarrow 3Fe^{2+} + 6e^-$$

$$C_2HCl_3 + 3H^+ + 6e^- \rightarrow C_2H_4 + 3Cl^-$$
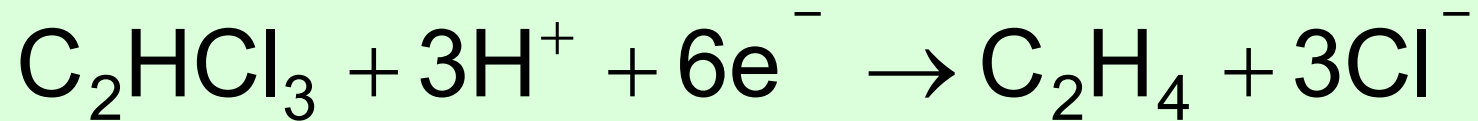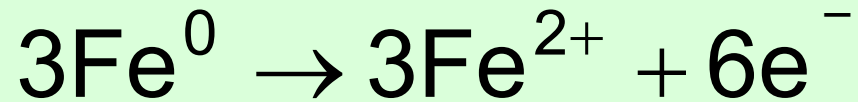
End products are chloride and ethane

Zero-valence iron wall

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

SAND

Sample Port

GRANULAR

IRON

Sampling Needle

SAND

Collapsible Teflon™ Bag Containing Groundwater

Typical Column Setup

Pump
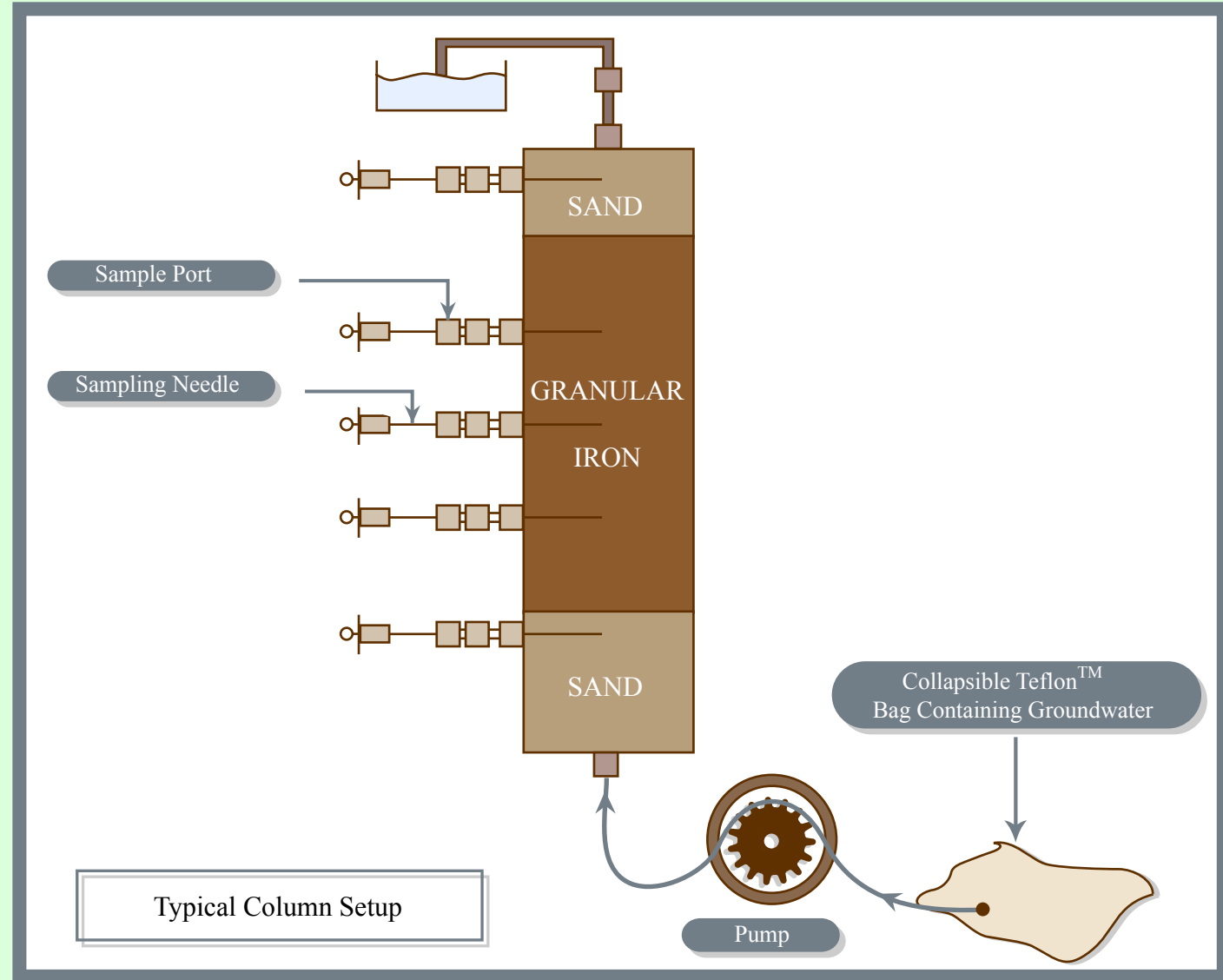
Analysis of column-test results

Analyze column-test results to find k:
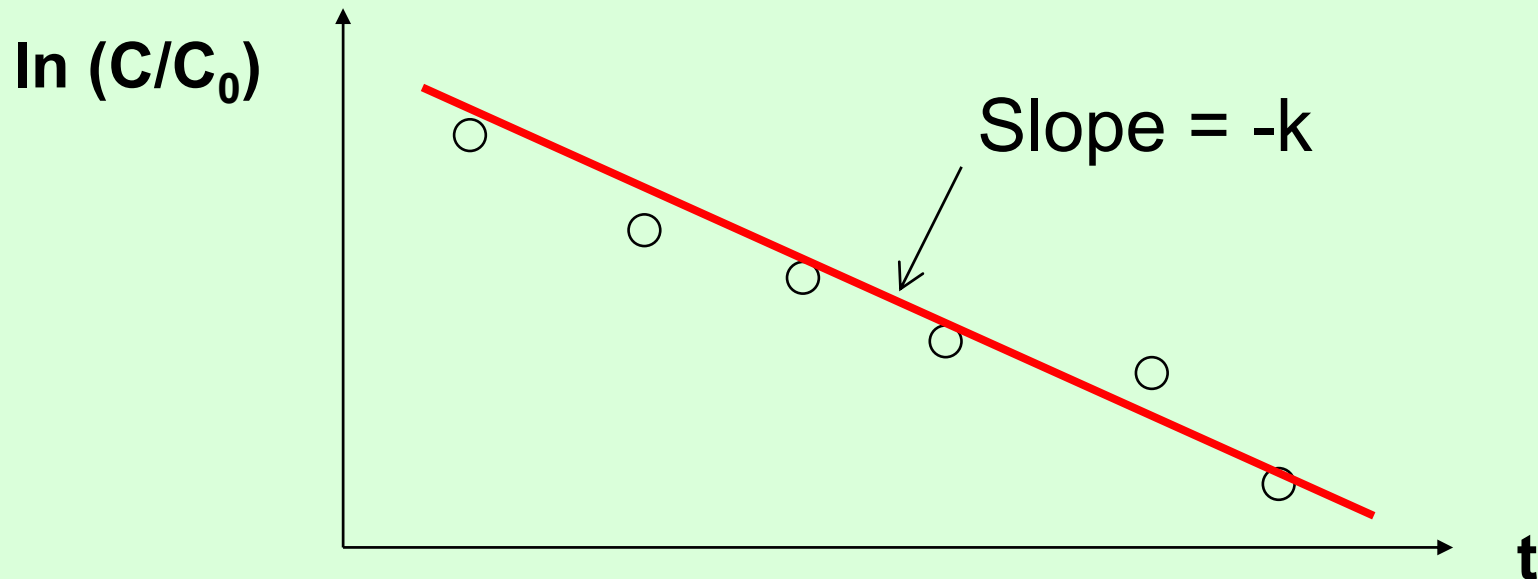
Reaction half-life, $t_{1/2} = 0.69 / k$

Design of treatment walls

Determine desired residence time, τ, in reactive wall based on desired C_{end}, known C_0

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

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:

t½ = 1 hr
u = 2 ft/day

Wall thickness =
1 foot

Chart: Required Wall Thickness (ft.) vs. Groundwater Velocity (ft./day), C/C$_0$ = 1/1000

Legend: — t$_{1/2}$ = 10 hr. — t$_{1/2}$ = 4 hr. — t$_{1/2}$ = 1 hr. — t$_{1/2}$ = 15 min.
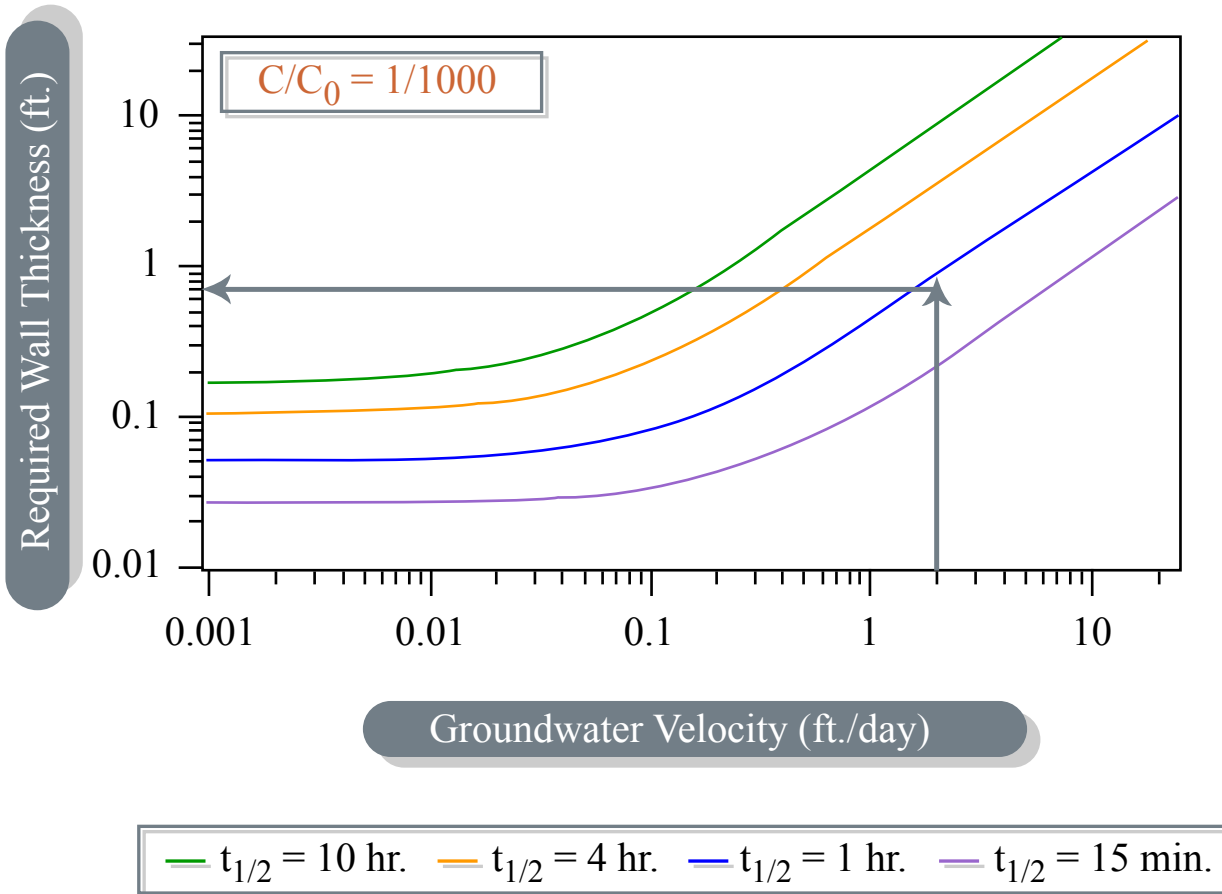
Adapted from: Eykholt, G. R. and T. M. Sivavec. "Contaminant Transport Issues for Reactive-Permeable Barriers." *Geoenvironment 2000* (Characterization, Containment, Remediation, and Performance in Environmental Geotechnics); Proceedings of a Specialty Conference held in New Orleans, Louisiana, February 24-26, 1995. New York: American Society for Civil Engineers, pp. 1608-1621.

PRB Effectiveness Over Time

See Figure 6 in: Jörg Klausen, Peter J. Vikesland, Tamar Kohn, David R. Burris, William P. Ball, and A. Lynn Roberts, 2003. Longevity of Granular Iron in Groundwater Treatment Processes: Solution Composition Effects on Reduction of Organohalides and Nitroaromatic Compounds. Environmental Science and Technology, Vol. 37, No. 6, Pp. 1208 -1218. March 15, 2003.

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

Bowles, M. W., L. R. Bentley, B. Hoyne and D. A. Thomas, 2000. "In Situ Ground Water Remediation Using the Trench and Gate System." *Ground Water*, Vol. 38, No. 2, Pp. 172-181.

Installation can include deep soil mixing, slurry technologies (including "biopolymers"), or removable modules of treatment media

Funnel and Gate System

See image at the Web site of Ontario Centre for Environmental Technology Advancement, Technology Profile Catalogue, Waterloo Barrier™ for Groundwater Containment. http://www.oceta.on.ca/profiles/wbi/barrier.html Accessed May 11, 2004.

Permeable Reactive Barrier Installation

See images at the Web site of EnviroMetal Technologies
Inc., http://www.eti.ca/Construction.html
Accessed May 11, 2004.

Bio-Polymer Installation of PRB

See image of Permeable Reactive Barrier Installation by the Bio-Polymer Slurry Method at the Web site of Geo-Con, Environmental Construction and Remediation, In-Situ Soil Stabilization, Shallow Soil Mixing, http://www.geocon.net/envprb7.asp. Accessed May 11, 2004.

Alternative PRB treatment media

Wood chips – nitrate removal

Robertson, W. D., D. W. Blowes, C. J. Ptacek and J. A. Cherry, 2000. "Long-Term Performance of In Situ Reactive Barriers for Nitrate Remediation." *Ground Water*, Vol. 38, No. 5, Pp. 689-695.

Iron – chromium VI reduction to Cr(III)

Blowes, D. W., C. J. Ptacek and J. L. Jambor, 1997. "In-Situ Remediation of Cr(VI)-Contaminated Groundwater Using Permeable Reactive Walls: Laboratory Studies." *Environmental Science & Technology*, Vol. 31, No. 12, Pp. 3348.

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

Iron slag – phosphorus

Los Alamos National Laboratory

Source: Los Alamos National Laboratory (see notes).

Multi-media PRB at Los Alamos, NM

Installed across canyon downstream of wastewater discharge from Radioactive Liquid Waste Treatment Facility
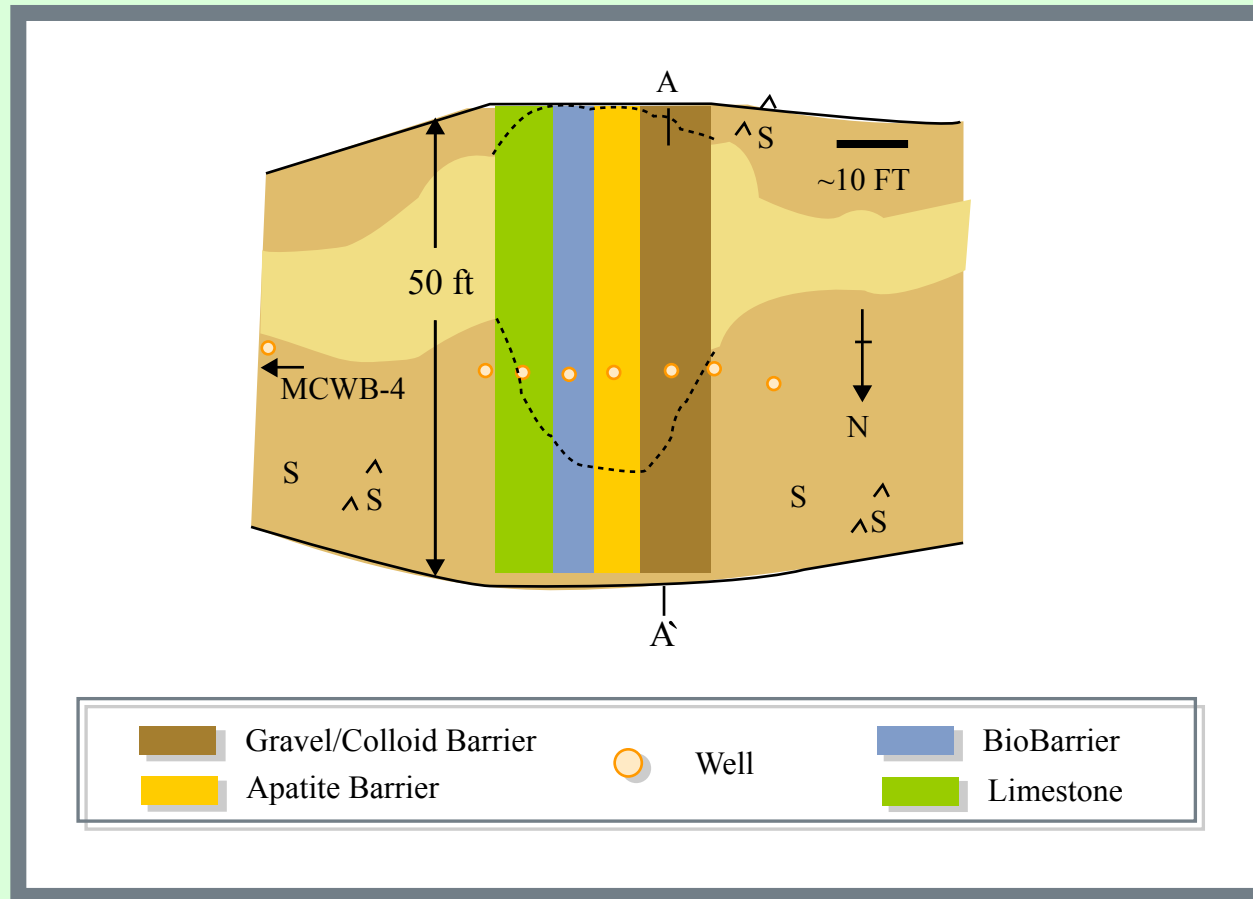
Designed to treat:

strontium-90; americium-241; uranium;

plutonium-238, -239 and -240;

perchlorate; nitrate;

heavy metals

Downstream view of multi-media PRB

A

A`

S

^

G-C

10 ft

| | Tuff | | Sandy Silt and Clay | | Alluvium | | Boulder Cover |
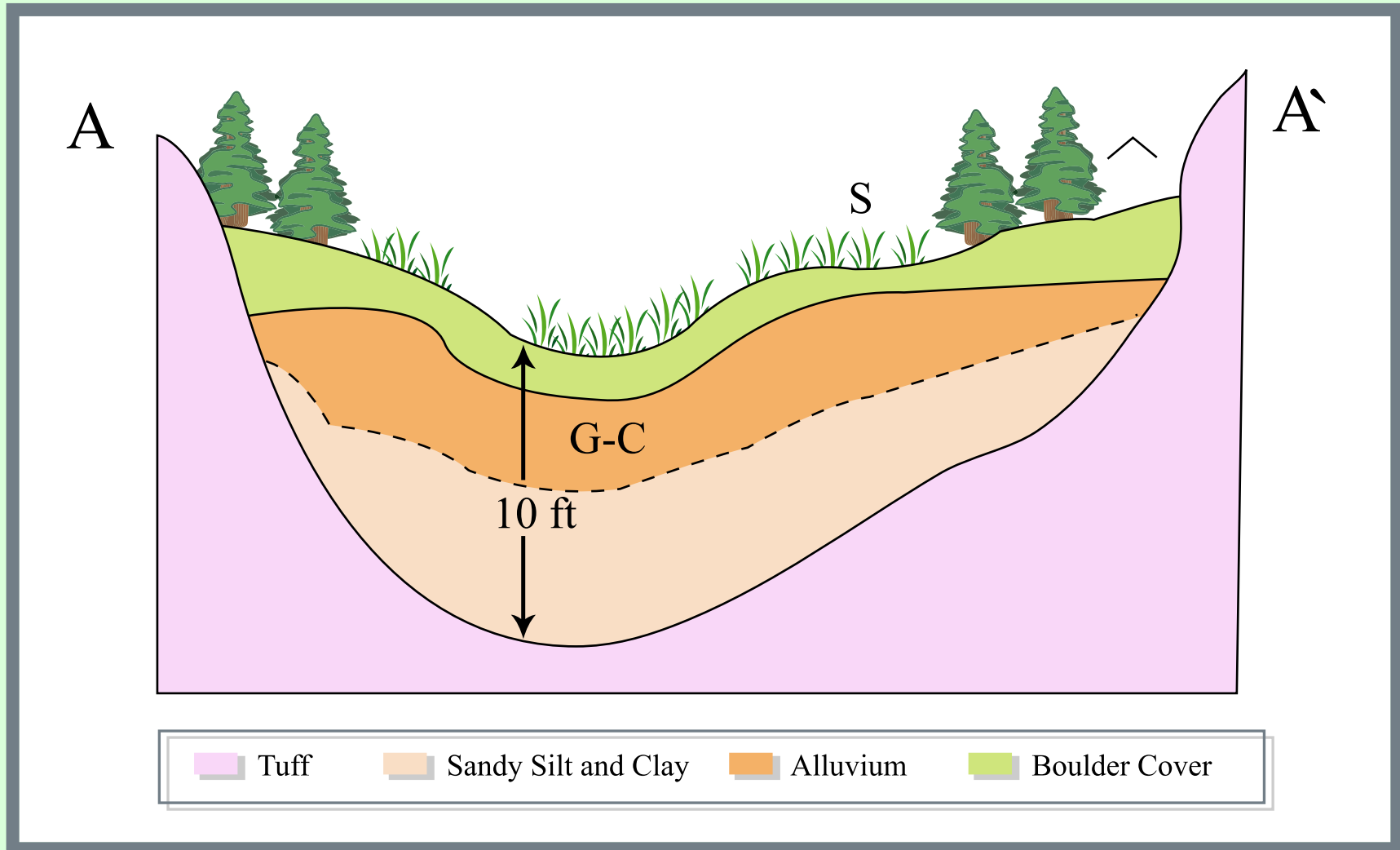
Side view of multi-media PRB

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.

Photo Credit: Courtesy of RRES Division

Source: Los Alamos National Laboratory (see notes), http://www.lanl.gov/worldview/news/images/prb.jpg. Accessed May 11, 2004.

Permeable reactive barriers

For more information:

A.R. Gavaskar, N. Gupta, B.M. Sass, R.J. Janosy, and D. O'Sullivan, 1998. *Permeable Barriers for Groundwater Remediation*. Battelle Press, Columbus, Ohio.

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

Source: Van Deuren, J., T. Lloyd, S. Chhetry, R. Liou, and J. Peck, 2002. Remediation Technologies Screening Matrix and Reference Guide, 4th Edition. Federal Remediation Technologies Roundtable.