Vapor Intrusion Fundamentals

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This training focuses on some of the basic principles that need to be understood in order to understand and effectively manage the vapor intrusion pathway.

Lecture notes are at the bottom of each slide so that if played out as a hard-copy, the presentation can be a useful reference document.

Some Fundamentals

- Units
- Fick's Law
- Contaminant Partitioning
- Attenuation (alpha) Factors
- Site Conceptual Model (SCM, CSM)
- Risk Based Screening Levels
- Bioattenuation

This is a summary of the topics we will cover. Some of these principles you may not have had in school or have never really used them, so you are rusty. We will be using them throughout the rest of this seminar so we will review them now.

The Most Common Goof

1 ug/L Benzene equals:

a) 1 ppbv

b) 1 ppmv

c) 330 ppbv

d) None of the Above

Vapor units is one of the most common mistakes being made by practitioners in this field. Let's see how you do:

Another Common One:

100 inch of Water = ? Inches of Hg

a) 5
b) 8
c) 10
d) 15

Another one.

How do Contaminants Move?

Movement (Flux) = K d?/dx

where: K is a proportionality constant
d?/dx is a gradient

| Property	Equation	Constant
Momentum:	Flux = K dH/dx	hydraulic cond
Heat (Poisson's):	Flux = Φ dT/dx	thermal cond
Mass (Fick's):	Flux = D dC/dx	diffusivity

Momentum, Heat, Mass ALL Move from High to Low

The fundamental equation describing momentum, heat, and mass movement is the same. Movement or flux is equal to a proportionality constant times a gradient. For momentum (groundwater or balls), the equation is known as Darcy's Law. For heat, the equation is known as Poisson's Law. For mass, it is known as Fick's Law. The proportionality constant is known as the diffusivity or diffusion coefficient (D).

Balls, heat, and mass all move the same way: downhill, hot to cold, high to low concentration. As you will see, people often tend to forget this fundamental concept and make incorrect decisions.

Common Vapor Profiles
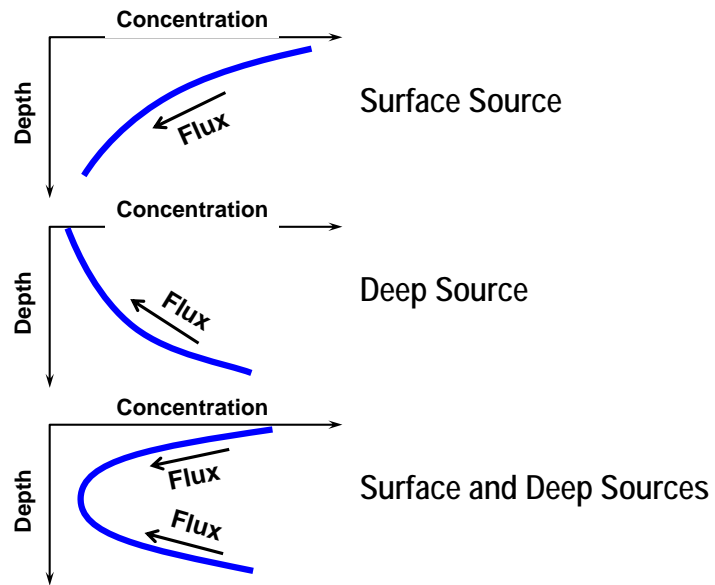
Knowledge of Fick's Law enables one to determine the direction of soil gas movement, and hence the direction of the source, from vertical gradients of the soil gas. Three types of common profiles are shown for sources at different locations in the vadose zone. Note that the flux is down the concentration gradient even when the flux is going "uphill" with respect to depth in the vadose zone.

Contaminant Partitioning
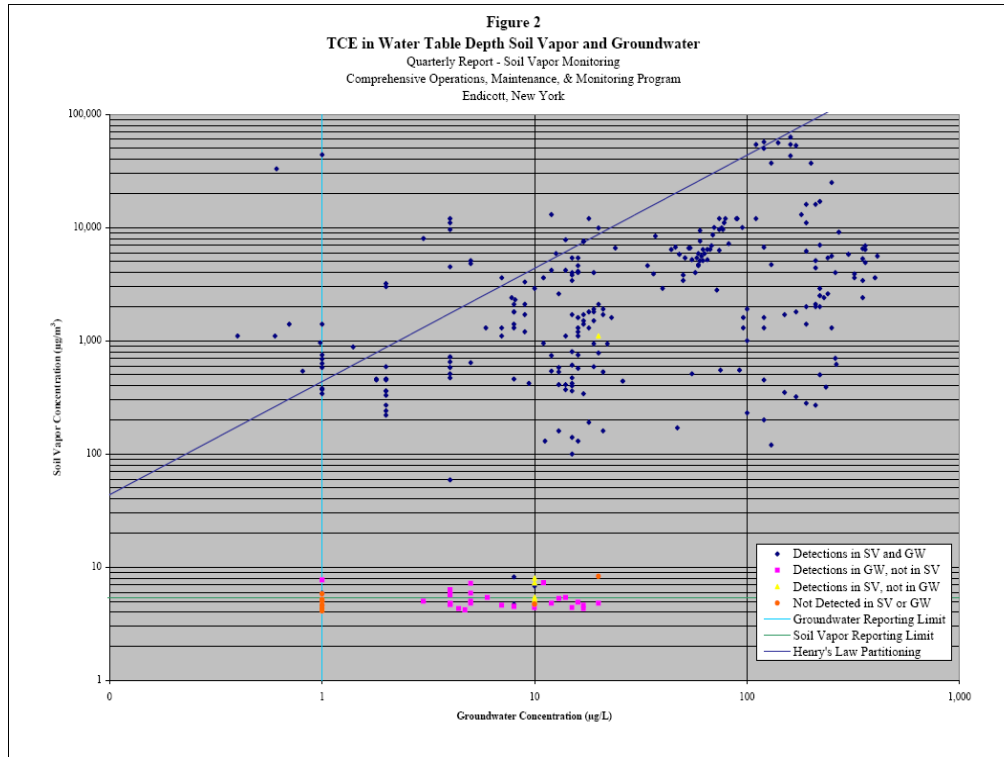
Groundwater to Soil Gas (Henry's Constant):

$$H = Csg/Cw, \text{ so, } Csg = Cw * H$$

Example: $H_{benzene} = 0.25$ (dimensionless)
For GW Conc = 10 ug/L
Csg = 10 * 0.25 = 2.5 ug/L

**Assumes Equilibrium. Very Rarely Achieved
(no mixers or blenders in the subsurface)**

Partitioning refers to the distribution of molecules between different phases. Partition coefficients are determined empirically by laboratory measurement. The partition coefficient for water to air partitioning (e.g., groundwater to soil gas) is called the Henry's Constant or Henry's Law. It simply is a ratio of the concentration in the air to the concentration in the water. It is simple to calculate the soil gas concentration from groundwater data or the reverse from the dimensionless Henry's constant.
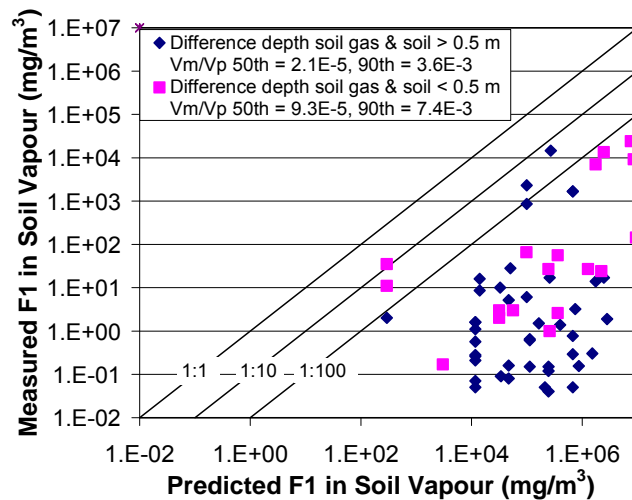
Henry's constants are based upon equilibrium being reached. The container was vigorously mixed. Mixers do not exist in the subsurface so equilibrium not reached and actual soil gas concentrations are far below calculated ones.

Figure 2
TCE in Water Table Depth Soil Vapor and Groundwater
Quarterly Report - Soil Vapor Monitoring
Comprehensive Operations, Maintenance, & Monitoring Program
Endicott, New York

This slide shows data from the NY Endicott site comparing measured soil gas concentrations near groundwater to groundwater concentrations. The line shows the predicted values based upon equilibrium partitioning using the Henry's constant. You can see that the vast majority of points fall orders of magnitude below the calculated values. This proves that soil gas values predicted by groundwater are over-estimated.

Slide courtesy of Dr. William Wertz, NYDEC

Measured Soil Gas Data vs. Predicted from Soil Phase Data

Measured F1 in Soil Vapour (mg/m³)

1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02

♦ Difference depth soil gas & soil > 0.5 m
Vm/Vp 50th = 2.1E-5, 90th = 3.6E-3
■ Difference depth soil gas & soil < 0.5 m
Vm/Vp 50th = 9.3E-5, 90th = 7.4E-3

1:1   1:10   1:100

1.E-02   1.E+00   1.E+02   1.E+04   1.E+06

Predicted F1 in Soil Vapour (mg/m³)

CPPI Database

.005

Key point:	Measured vapor concentrations 10 to 1000x less than predicted

This slide compares measured soil gas concentrations to soil gas concentrations predicted from co-located soil phase data for petroleum hydrocarbons. You can see that the vast majority of measured values fall orders of magnitude below the calculated values. This proves that soil gas values for hydrocarbons predicted from soil data are likely to be over-estimated. The same is not necessarily true for chlorinated solvents.

Slide courtesy of Ian Hers, Golder and Associates.

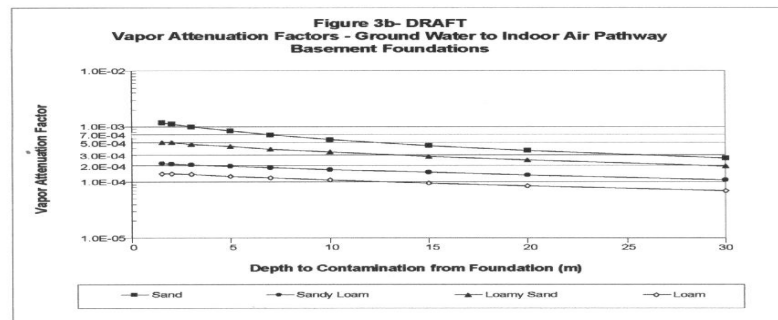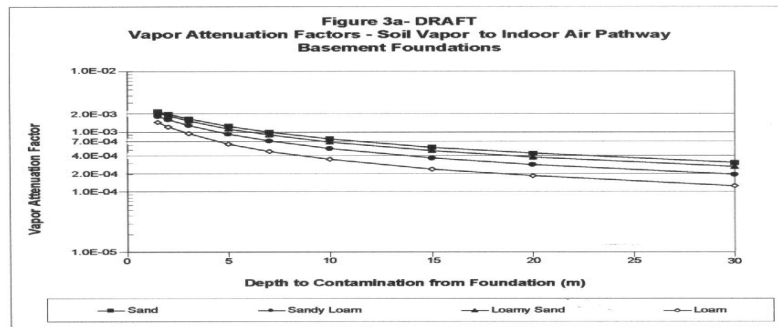## Attenuation (alpha) Factors

$$\alpha_{sg} = C_{indoor}/C_{sg}$$
$$\alpha_{gw} = C_{indoor}/(C_{gw}*H)$$

- Lower alpha means higher attenuation
- Current VI guidances:
  - EPA α_{sg} = 0.002 for 5', 0.1 for sub-slab
  - CA α_{sg} = 0.002 for 5', 0.01 for sub-slab
  - NY State Data Shows α_{sg} < 0.01
  - Hydrocarbon α_{sg} likely <0.0001

A common term in the vapor intrusion "community" is the attenuation factor also called the alpha factor. The soil gas alpha factor is a ratio of the indoor air concentration to the soil gas concentration. The groundwater alpha factor is a ratio of the indoor air concentration to the groundwater concentration times its Henry's constant.

Since indoor air values are lower than subsurface values, alpha factors tend to be less than 1, hence lower numbers mean greater attenuation. Thus, inverse alpha factors are often easier to understand.

The EPA draft guidance uses very stringent alpha factors, determined empirically from a limited data base. More recent and larger data bases (IBM Endicott) are showing that the alphas should be orders of magnitude lower, especially for petroleum hydrocarbons.

Figure 3a- DRAFT
Vapor Attenuation Factors - Soil Vapor to Indoor Air Pathway
Basement Foundations

Figure 3b- DRAFT
Vapor Attenuation Factors - Ground Water to Indoor Air Pathway
Basement Foundations

In the draft VI guidance, alpha factors can are summarized vs. depth in Figure 3. As you can see in Figure 3a, the highest soil gas alpha is 0.002 at 5 feet below the structure. The inverse is 500.

For groundwater, Figure 3b shows the highest alpha is ~.001. The inverse is 1000.

SITE 2: Indoor Air & Sub-slab Vapor -- TCE
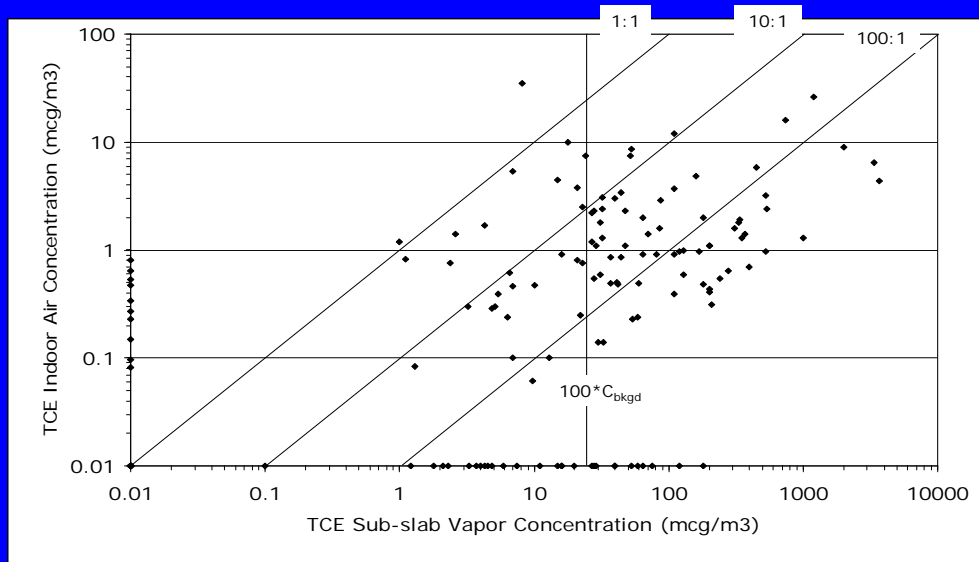
Alpha factors from the NY Endicott site show large variation from 1 to 0.001 further complicating what value to use in interpreting sub-slab soil gas results.

Conceptual Site Model
(or Site Conceptual Model?)

DEFINITION:

A Conceptual Site Model (CSM) is a simplified version (pictures and/or descriptions) of a complex real-world system that approximates its relationships
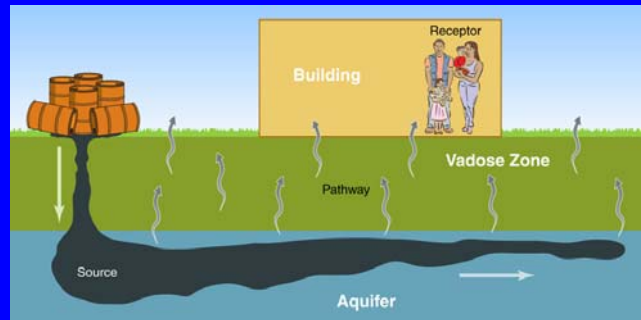
A site conceptual model is a basic picture of the sit.

Key information required:

•What types of contaminants at what concentrations in what media?

•Is contamination well defined?

•What types of receptors (houses, retail, commercial industrial) and what structure type (slab, basement, crawlspace)?

•What is location of contaminant relative to structure?

•Is the Risk Acute?

Components of a CSM

- Existing & potential future buildings

- Construction of buildings

- Type of HVAC system

- Soil stratigraphy – Are Soils Clean?

- Hydrogeology & depth to water table

- Receptors present (sensitive?)

- Nature of vapor source

- Vadose Zone characteristics

- Limits of source area & contaminants of concern

- Surface cover description in source and surrounding area

What is Missing From This Checklist?

Some of the components of a SCM. Go to the ITRC guidance for a complete checklist.

RISK 101:
Screening Level Acronyms

- RBSL: Risk Base Screening Level
- RBC (from ASTM): Risk Based Concentration
- CHHSL: CA Human Health Screening Level
- Region 3 Screening Levels (RSLs)

Need to Know When & How to Use

Risk based screening levels vary from state to state and guidance to guidance. Acronyms are plentiful. The VI professional needs to know what they are, where they come from, and how and when to use them.

What Risk Level?

- 1 in 1 million: Residences, Schools, Hosp
- 1 in 100,000: Commercial Settings (cumulative)
- 1 in 10,000: Acute (mitigate immediately & in some states evacuate premises)

The allowable concentrations in indoor air, and hence in the vadose zone, depend upon the risk level and exposure time. Different agencies use different risk levels.

Risk Ranges & Action

For carcinogens, the human health screening levels presented are based on a target excess cancer risk of 10^{-6}. This represents the upper end (most stringent) of the potentially acceptable range of 10^{-4} to 10^{-6} recommended by the USEPA (USEPA 1989a,b). As stated in the National Contingency Plan, however, "The 10^{-6} level shall be used as the point of departure for determining remediation goals..." (USEPA 1994). Remediation or risk management is rarely warranted at sites where the estimated cancer risk does not exceed 10^{-6}. Remediation or risk management is almost always warranted at sites where the estimated cancer risk exceeds 10^{-4}. For sites where the estimated risk is between 10^{-4} and 10^{-6}, the need for active remediation or risk management is evaluated on a site-specific basis (i.e., risks within this range are "potentially acceptable", depending on site-specific considerations).

This text from the US EPA gives direction on when to take action for different exceedances of risk levels

RISK 101:

Why Are Indoor Air RBSLs So Low?

- Benzene: EPA: 0.31 ug/m3
- TCE: EPA: 0.022 or 1.0 ug/m3
- PCE: EPA: 0.41 ug/m3
- Values Assume Exposure Times of:
    - 24 hr, 350 days/yr, 30 years

Ultra Conservative Assumptions Lower Allowed Levels and Bring in More Sites

Allowable indoor air concentrations are so low because of the ultra conservative assumptions that are used, especially in regards to exposure time.

Example Exposure Parameters

Parameter	Symbol	Typical Value	Units
Target Risk	TR	1E-6, 1E-5	unitless
Body Weight	BW	70	kg
Averaging Time-cancer	AT_C	25,550	days
Averaging Time-noncancer	AT_{NC}	ED x 365	days
Conversion Factor	CF	1,000	μg/mg
Exposure Duration	ED	25	years
Exposure Frequency	EF	250	days/year
Intake Rate	IR	20	m^3/day
Attenuation Factor	α	.01-.0001	unitless

Typical parameters used in calculations of RBSLs

Inhalation Exposure Parameters

20 m³/day for Res. *vs* Comm.-Ind. Exposure				
Parameter	Symbol	Res.	Comm-Ind.	Units
Exposure Duration	ED	30	25	years
Exposure Frequency	EF	350	250	days/year
Exposure Time	ET	24	8	hours/day

$$\left(\frac{Residential}{Comm-Ind}\right) = \left(\frac{30\ years}{25\ years}\right) \times \left(\frac{350\ days/year}{250\ days/\ year}\right) \times \left(\frac{24\ hours/day}{8\ hours/day}\right) = 5.1 \cong \mathbf{5}$$

Exposure parameters may be set by EPA policy or guidance; state policy, legislation, regulation, or guidance; or even County or local requirements. Federal facilities are likely to have their own exposure factors because of the shorter military-specific tours of duty at any one base or facility. Be sure to check the requirements of the applicable agency for your case.

The ratio of inhalation exposure factors for residential and commercial-industrial exposure scenarios has a "standard" ratio of 5. To convert an RBSL for a residential scenario to one for a commercial-industrial scenario, the residential RBSL would be multiplied by a factor of 5 to obtain the RBSL for a Commercial-Industrial exposure scenario.

Methods for RBSL Determination

- From Lookup Tables
- From Attenuation Factor
- From Spreadsheet/Model

Method Often Agency Specific

There are 3 common ways to determine screening levels.   Lookup tables are typically the most conservative; spreadsheets the least conservative.

RBSLs from Lookup Tables

- Often Very Conservative
- Considered for "Generic Site"
- Often Derived by Johnson-Ettinger Model
- Generally Not Used for New Data

Lookup tables are offered in the EPA-OSWER guidance and by many State agencies. They are typically the most conservative screening levels

Table 2. California Human Health Screening Levels for Indoor Air and Soil Gas

Chemical	[1]Indoor Air Human Health Screening Levels (µg/m³)		[2]Shallow Soil Gas Human Health Screening Levels (Vapor Intrusion) (µg/m³)	
	Residential Land Use	Commercial/Industrial Land Use Only	Residential Land Use	Commercial/Industrial Land Use Only
Benzene	8.40 E-02	1.41 E-01	3.62 E+01	1.22 E+02
Carbon Tetrachloride	5.79 E-02	9.73 E-02	2.51 E+01	8.46 E+01
1,2-Dichloroethane	1.16 E-01	1.95 E-01	4.96 E+01	1.67 E+02
cis-1,2-Dichloroethylene	3.65 E+01	5.11 E+01	1.59 E+04	4.44 E+04
trans-1,2-Dichloroethylene	7.30 E+01	1.02 E+02	3.19 E+04	8.87 E+04
Ethylbenzene	Postponed[3]	Postponed[3]	Postponed[3]	Postponed[3]
Mercury, elemental	9.40 E-02	1.31 E-01	4.45 E+01	1.25 E+02
Methyl tert-Butyl Ether	9.35 E+00	1.57 E+01	4.00 E+03	1.34 E+04
Naphthalene	7.20 E-02	1.20 E-01	3.19 E+01	1.06 E+02
Tetrachloroethylene	4.12 E-01	6.93 E-01	1.80 E+02	6.03 E+02
Tetraethyl Lead	3.65 E-04	5.11 E-04	2.06 E-01	5.78 E-01
Toluene	3.13 E+02	4.38 E+02	1.35 E+05	3.78 E+05
1,1,1-Trichloroethane	2.29 E+03	3.21 E+03	9.91 E+05	2.79 E+06
Trichloroethylene	1.22 E+00	2.04 E+00	5.28 E+02	1.77 E+03
Vinyl Chloride	3.11 E-02	5.24 E-02	1.33 E+01	4.48 E+01
m-Xylene	7.30 E+02	1.02 E+03	3.19 E+05	8.87 E+05
o-Xylene	7.30 E+02	1.02 E+03	3.15 E+05[4]	8.79 E+05[4]
p-Xylene	7.30 E+02	1.02 E+03	3.17 E+05	8.87 E+05

Reference: Appendix 1, OEHHA Target Indoor Air Concentrations and Soil-Gas Screening Numbers for Existing Buildings under Residential and Industrial/Commercial land uses.
Notes:
1. "Residential Land Use" screening levels generally considered adequate for other sensitive uses (e.g., day-care centers, hospitals, etc.). Commercial/industrial properties should be evaluated using both residential and commercial/industrial CHHSLs. A deed restriction that prohibits use of the property for sensitive purposes may be required at sites that are evaluated and/or remediated under a commercial/industrial land use scenario only.
Calculation of cumulative risk may be required at sites where multiple contaminants with similar health effects are present.
Carcinogens: CHHSLS based on target cancer risk of 10-6. Cal/EPA cancer slope factors used when available.
Noncarcinogens: CHHSLS based on target hazard quotient of 1.0.
2. Soil Gas: Screening levels based on soil gas data collected <1.5 meters (five feet) below a building foundation or the ground surface. Intended for evaluation of potential vapor intrusion into buildings and subsequent impacts to indoor-air. Soil gas data should be collected and evaluated at all sites with significant areas of VOC-impacted soil. Screening levels also apply to sites that overlie plumes of VOC-impacted groundwater.
3. Calculation of a screening number for the chemical has been postponed (pp) until the toxicity criterion currently being developed by OEHHA is published as a final document.
4. Representative Screening Numbers for mixed xylenes. The representative value for mixed xylenes is based on the calculated lowest one amongst the three isomers.

The California Human Health Screening Levels (CHHSLs) were developed by a branch of CA-EPA (OEHHA) using the Johnson-Ettinger model. Note, soil gas values are for 5' deep soil gas samples, not for sub-slab samples.

Using Alpha Factors to Calculate Screening Levels

For Soil Gas:

$$C_{sg} = C_{indoor}/\alpha_{sg}$$

For Groundwater:

$$C_{gw} = C_{indoor}/(H*\alpha_{gw})$$

Example: C_{in} benzene = 0.3 ug/m3
C_{sg} (5') = 0.3/0.002 = 150 ug/m3
C_{gw} = 0.3/(0.20* 0.0005) = 30 ug/L

By using attenuation (alpha factors) one can calculate screening levels for soil gas and groundwater by knowledge of the acceptable indoor air concentration.

Many consultants are not familiar with using alphas and calculate incorrect target values.

RBSLs from Models

- Johnson-Ettinger Most Common
  - GW, soil, soil gas spreadsheets
  - Least conservative RBSLs
  - No bioattenuation component
- Biovapor
  - J-E model with bioattenuation added
  - Oxygen mass-balnace
  - In Beta testing by EPA
  - Will be available from API

Several models are available that allow you to calculate screening values for groundwater, soil gas, and even soil phase data. The Johnson-Ettinger model/spreadsheet is the most common. API is releasing a version that includes bioattenuation.
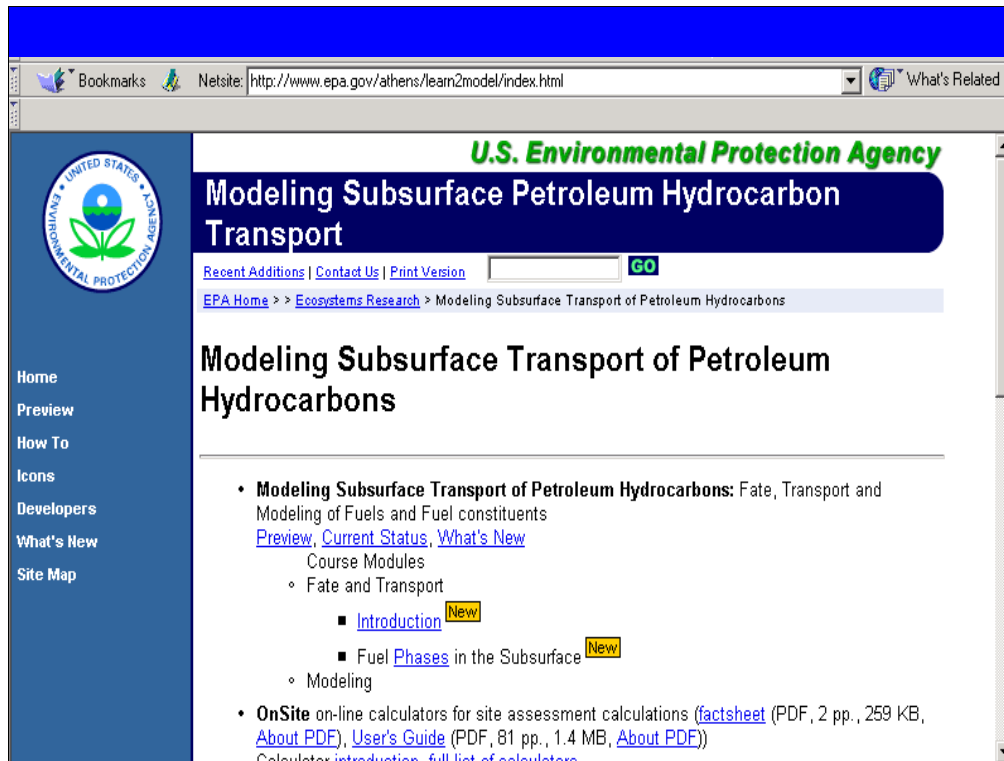
This on-line calculator is a handy way to get a feel for "fail levels" without getting into the J-E spreadsheets. It uses EPA Federal default parameters for toxicity info, ventilation rates, etc. It can be found at http://www.epa.gov/athens/learn2model/index.html.

Comparison: Benzene in Soil Gas, Residential Receptor, 1-6 Risk

	Alpha	1/Alpha	RBSL (ug/m^3)
CHHSL	0.002		37
DTSC – S5	0.002	500	42
DTSC – S6	Model	1000	95
EPA Q5	0.002	500	155

A comparison of the different screening levels from the different approaches.

Example: RBC for Benzene in Soil Gas, Commercial Receptor

Allowable indoor air residential level: $0.084 \mu g/m^3$

- For commercial receptors use 100,000 risk, hence allowable indoor commercial level = $0.84 \ \mu g/m^3$
- Adjust for 5 times less exposure time for commercial:
  $5*0.84 = 4.2 \ \mu g/m^3$
- Adjust for 2 times higher exchange rate for commercial,
  $2*4.2 = 8.4 \ \mu g/m^3$

Default attenuation factor for soil gas from 5' bgs= 0.002, hence allowable soil gas conc:

$$Csg= 8.4/0.002 = 4200 \ \mu g/m^3 = 4.2 \ ug/L$$

Calculating a soil gas screening level from allowed indoor air level.

Other Considerations

- Toxicity of Compounds
  - TCE: 0.017 or 1.0 $\mu g/m^3$ (50x)
  - Benzene: 0.084 or 0.31 $\mu g/m^3$ (~4x)

- Cumulative Risk – Required by some Agencies
  - Lowers RBSLs for each compound

Screen-Out More Sites By:

- Adopting More Realistic Exposure Times
  - Workplace: 8 hrs/day, 250 days/yr, 25 yrs (5x)
  - School: 8 hrs/day, 180 days/yr, 6 yrs (30x)
  - Hospital: 24 hrs/day, 1 yr (30x)

- Adopt More Reasonable Distance Criteria
  - 100' Spatial for HCs Too Far Due to Bio
  - 100' Vertical for Cl Too Far
  - 5-10' Vertical for HC if O2 Present

More sites will be screened out if more realistic screening criteria are used such as more realistic exposure times, especially for schools and hospitals, and adopting more reasonable depth criteria. For State reimbursement funds, reasonable screening of sites will prevent draining the fund balances.
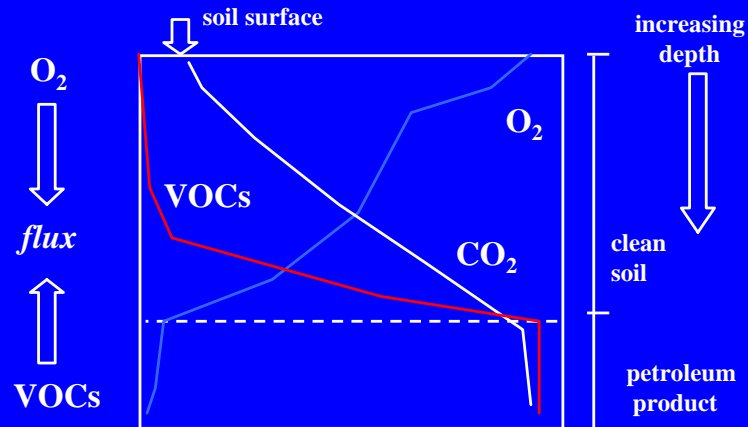
Bioattenuation of HCs

- Existing data suggest O_2 effective barrier
- Attenuation > 10,000 times
- Vertical profiles of COC & O_2
- How to Account for it?

A vast number of studies have been performed clearly demonstrating that the bioattenuation of hydrocarbon vapors occurs in aerobic soils. In general, the studies show that when oxygen levels are 10% or greater (a published study by NJDEP suggested oxygen levels as low as 6% are sufficient), and a couple feet of vadose zone exist between the source and receptor, that the hydrocarbons aren't escaping into the receptor. Attenuation factors can be as high as 10,000 times (alpha = 0.0001).

Documention that this process is occurring is done by collecting vertical profiles of the soil gas for the hydrocarbons, oxygen, and carbon dioxide. If shown to occur, many agencies are conservatively allowing a factor of 10 to 100 reduction in the alpha factor.

Theoretical Bio Profile

This is the theoretical profile for hydrocarbon VOCs, CO2, and oxygen in the soil gas with depth where bioattenuation is active. Without on-site analysis, you don't know where the depth of this zone is. Either use oxygen to find it or collect additional samples.
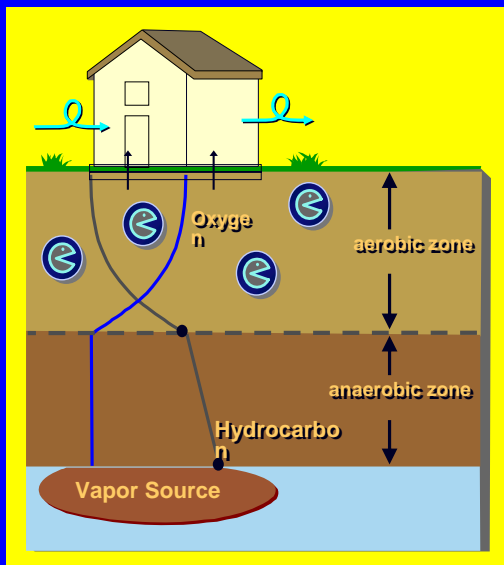
Conceptual model of the API Biovapor model/spreadsheet