Petroleum Vapor Intrusion from Subsurface to Indoor Air: Basics

in

Workshop 7: Assessment and Evaluation of Vapor Intrusion at Petroleum Release Sites

Tuesday, March 19, 2013; 6:30 pm to 9:30 pm

23rd Annual International Conference on Soil, Water, Energy, and Air

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Workshop Agenda

- Welcome, Introductions, Safety Issues
- Update on ITRC VI Workgroup
- Update on EPA OUST
- **PVI Overview;** BioVapor and other models; and Introduction to Exclusion Criteria
- Evaluating the Vapor Intrusion Pathway - Studies *45 minutes*
- Regulatory updates effecting sampling and Analysis
- Case Studies/ Lessons
- Summary

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Basics – Introduction – PVI Overview

To Be Covered:

- **Conceptual Models**
- **Biodegradation**
- **Building Foundations and Oxygen**

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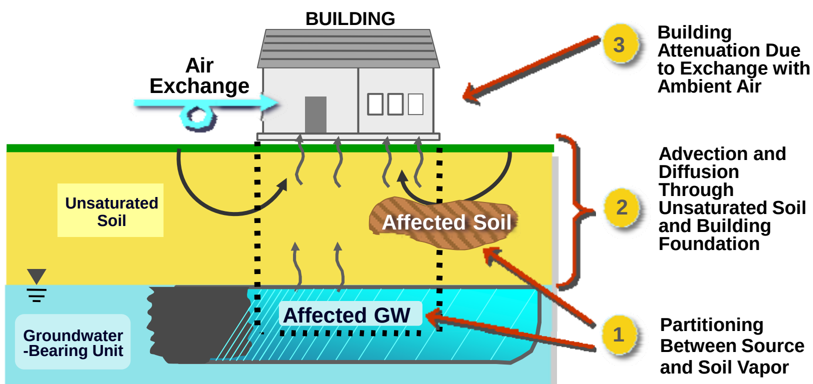
Conceptual Model for Vapor Intrusion:

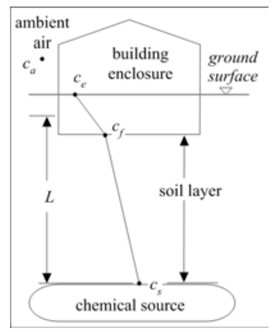
Regulatory Framework



KEY POINT: **Much of existing regulatory guidance is focused on building impacts due to vapor migration.**

Vapor Flow: Barriers and Limits

- Buildings
  - Air exchange, positive pressure, background
- Building Foundations
  - Intact (no cracks or unsealed penetrations)
- Vadose Zone
  - High soil moisture or clay (no vapor migration)
  - Aerobic biodegradation
  - Lateral offset
- Source and Groundwater
  - Clean water lens over source, Clay layers
  - Finite source mass, Saturated vapor limits



KEY POINT: Presence of subsurface source does not always result in observed vapor intrusion.

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Petroleum Hydrocarbons And Chlorinated Hydrocarbons Differ In Their Potential For Vapor Intrusion

USEPA OUST 2011, www.epa.gov/oust/cat/pvi/pvicvi.pdf

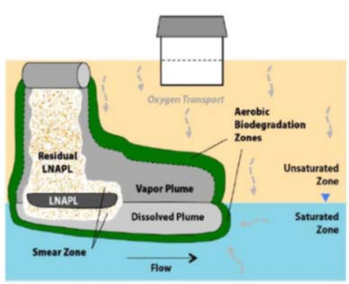

Figure 1. Typical petroleum hydrocarbon transport conceptual scenario

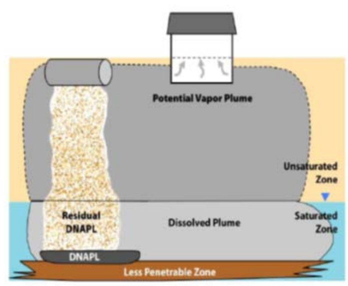

Figure 2. Typical chlorinated solvent transport conceptual scenario

KEY POINT: USEPA says that vapor intrusion risk is much lower at petroleum sites.

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Basics – Introduction - PVI

To Be Covered:

- Conceptual Models
- Biodegradation
- Building Foundations and Oxygen

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Petroleum VI - Biodegradation

- Biodegradation … is significant
  - Regulation & guidance:

    US EPA. 2002.

    US EPA. 2005. EPA/600/R-05/106.

    ITRC. 2007.

    US EPA. 2011.

    Others …

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Biodegradation of Petroleum Chemicals

In 100+ years of publications:

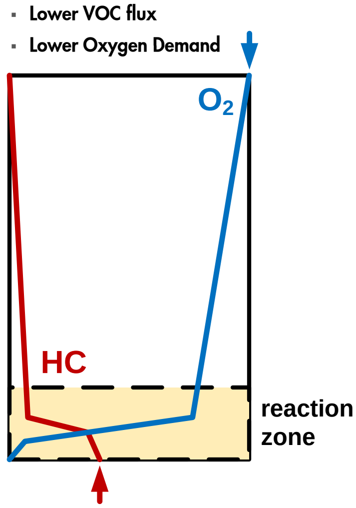
- **Biodegradation Reported for:**
  - solid, liquid, gases (methane & up)
  - straight, branched, ring(s), C-, C=;
  - by many species, 30+ genera bacteria, 25+ genera fungi, algae
    - not every chemical degraded by every species
  - marine, freshwater, sediments, soils
  - in direct metabolism and co-metabolism (co-oxidation)
  - Producing
    - Biomass
    - intermediate products (alcohols, aldehydes, organic acids)
    - ultimate mineral products: CO_2, H_2O

Reviews of petroleum biodegradation:
Zobell, C. E., *Bacteriological Reviews*, **1946**, 10(1-2): 1–49. 182 refs.
Atlas, R. M., *Microbiological Reviews*, **1981**, 180-209. 305 refs.
Leahy, J. G.; Colwell, R. R., *Microbiological Reviews*, **1990**, 305-315. 157 refs.

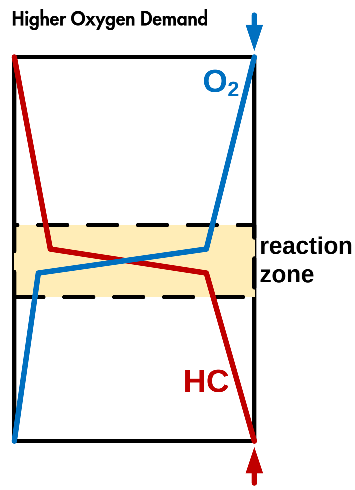
- **Observations:**
  - Fast acclimation times
    - absent other limits, by:
      - population enrichment (fast biomass growth)
      - and/or plasmid transfer
      - acclimation times can be affected by prior exposure
  - Environmental Conditions:
    - 0°< to 70°C
    - salinity up to 25% NaCl
    - pH from 6 to 10
    - optimum conditions can be narrower
  - Redox Conditions
    - Aerobic
      - equally good in range from 0.5 to 30 mg/L aqueous dissolved oxygen
    - Anaerobic
      - observed, not ubiquitous
      - other electron acceptors present (nitrate, sulfate, etc.) [strict or facilitative], or
      - including fermentive / methanogenic conditions

Observed Soil Gas Profiles

- Lower Concentration Source
  - Dissolved Groundwater Source
  - Clean Soil Model
  - Lower VOC flux
  - Lower Oxygen Demand



- Higher Concentration Source
  - LNAPL Source
  - Dirty Soil Model
  - Higher VOC Flux
  - Higher Oxygen Demand



Aerobic Biodegradation in Soils: Factors

Food (Substrate)
Energy for growth and maintenance
Bioavailable (water-phase) •

Biomass
Concentration
Species diversity
History (Acclimation)
Food to Biomass Ratio •
Nutrients

Oxygen
Presence •

Inhibition
Absence of Moisture •
Toxic Intermediate Compounds

Transport
Through bulk soil matrix

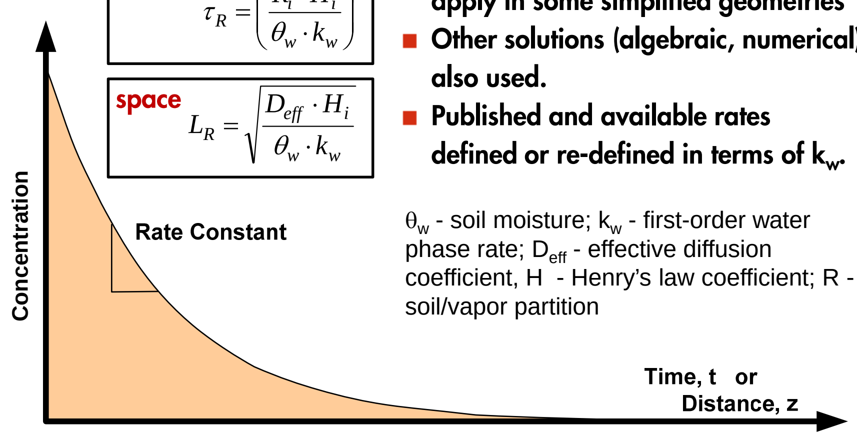
Diffusion within soil matrix (at and below scale of soil particles) •

Between chemical phases (water, soil gas, sorbed, LNAPL)

Exponential Decay: Data Analysis & Scaling

time $\tau_R = \left(\dfrac{R_i \cdot H_i}{\theta_w \cdot k_w}\right)$

space $L_R = \sqrt{\dfrac{D_{eff} \cdot H_i}{\theta_w \cdot k_w}}$

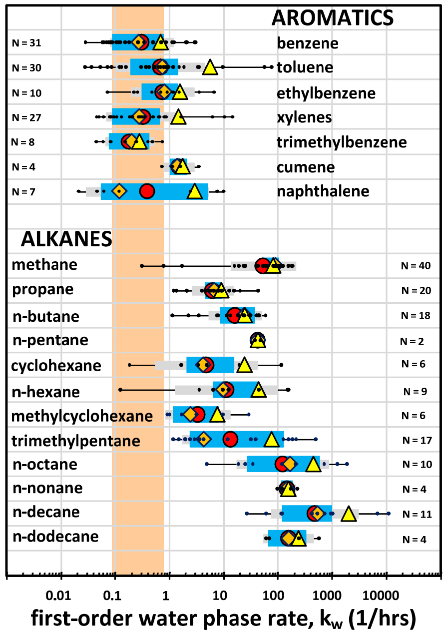


- Simple solutions (exponential decay) apply in some simplified geometries
- Other solutions (algebraic, numerical) also used.
- Published and available rates defined or re-defined in terms of k_w.

θ_w - soil moisture; k_w - first-order water phase rate; D_{eff} - effective diffusion coefficient, H - Henry's law coefficient; R - soil/vapor partition

other conditions similar: aerobic throughout

Results: Aerobic Petroleum Biodegradation Rates in Soil

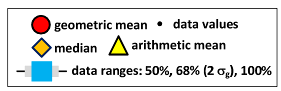


Aromatic Hydrocarbons

k_w = 0.48 /hr (0.08 to 3.0)

k_w = 40 /hr (7.8 to 205)

Aliphatic Hydrocarbons



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Data Sources: references

- **Field Data, Diffusive and Advective Columns, Batch Microcosms**

Field studies
1. Christophersen, M., et al., *J. Contaminant Hydrogeology*, **2005**, 81, 1-33.
2. Fischer, M. L., et al., *Environ. Sci. Technol.*, **1996**, 30, 10, 2948–2957.
3. Hers, I., et al., *J. Contaminant Hydrology*, **2000**, 46, 233-264.
4. Höhener, P., et al., *J. Contaminant Hydrology*, **2006**, 88, 337-358.
5. Lahvis, M. A., et al., *Water Resources Research*, **1999**, 35, 3, 753-765.
6. Lundegard, P. D., et al., *Environ. Sci. Technol.*, **2008**, Web 07/03/2008.

Diffusive soil columns and lysimeters
7. Andersen, R. G., et al., *Environ. Sci. Technol.,* **2008**, 42, 2575–2581.
8. DeVaull, G. E., et al., Shell Oil Company, Houston. **1997**.
9. Höhener, P., C. et al, *J. Contaminant Hydrology*, **2003**, 66, 93-115.
10. Jin, Y., T. et al., *J. of Contaminant Hydrology*, **1994**, 17, 111-127.
11. Pasteris, G., et al., *Environ. Sci. Technol.*, **2002**, 36, 30-39.

Advective columns
12. Salanitro, J. P., M. M. Western, Shell Development Company, Houston. **1990**, TPR WRC 301-89.
13. Moyer, E. E., PhD Thesis, University of Massachusetts, **1993**.
14. Moyer, E. E., et al., in In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes, R. E. Hinchee, et al, eds., (Battelle Press, Columbus), **1995**.

Microcosm studies
15. Chanton, J., et al., at: PERF Hydrocarbon Vapor Workshop, January 28-29, **2004**. Brea, CA.
16. Einola, J. M., et al., *Soil Biology & Biochemistry*, **2007**, 39, 1156–1164.
17. Fischer, M. L., et al., *Environ. Sci. Technol.*, **1996**, 30 (10), pp 2948–2957.
18. Holman, H. Y.; Tsang, Y. W., in In Situ Aeration: Air Sparging, Bioventing, and Related Bioremediation Processes, R. E. Hinchee, et al, eds., (Battelle Press, Columbus), 1995, 323-332.
19. Ostendorf, D. W., et al., *Environ. Sci. Technol.* **2007**, 41, 2343-2349.
20. Salanitro, J. P., Western, M. M., Shell Development Company, Houston, **1988**, TPR WRC 161-88.
21. Salanitro, J. P; Williams, M. P.; Shell Development Company, Houston, **1993**, WTC RAB 4-93.
22. Scheutz, C. et al., *J. Environ. Qual.* **2004**, 33:61-71.
23. Toccalino, P. L., et al., *Applied and Environmental Microbiology*, Sept. **1993**, 2977-2983.

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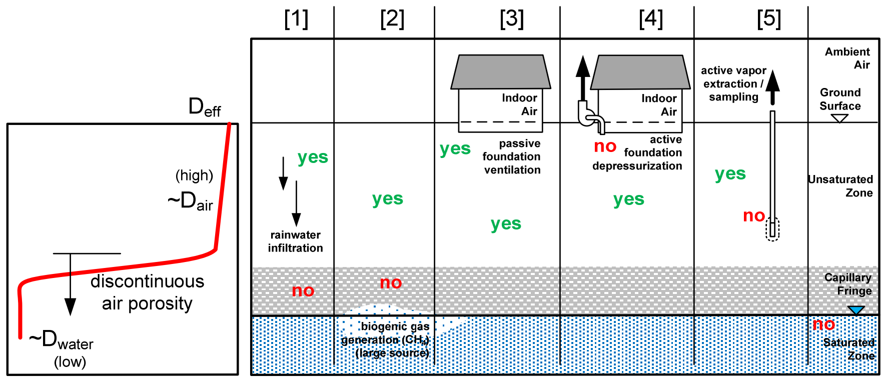
Constraints on Kinetic Data and Application



- Tabulated Rates Okay for Most Vadose Zone Soils
- Maybe Not: Near active vapor pumping points, capillary fringe, water-saturated soils, high NAPL loading. Due to:
  - Potential non-equilibrium local soil partitioning, or
  - Diffusion-limited biological reaction

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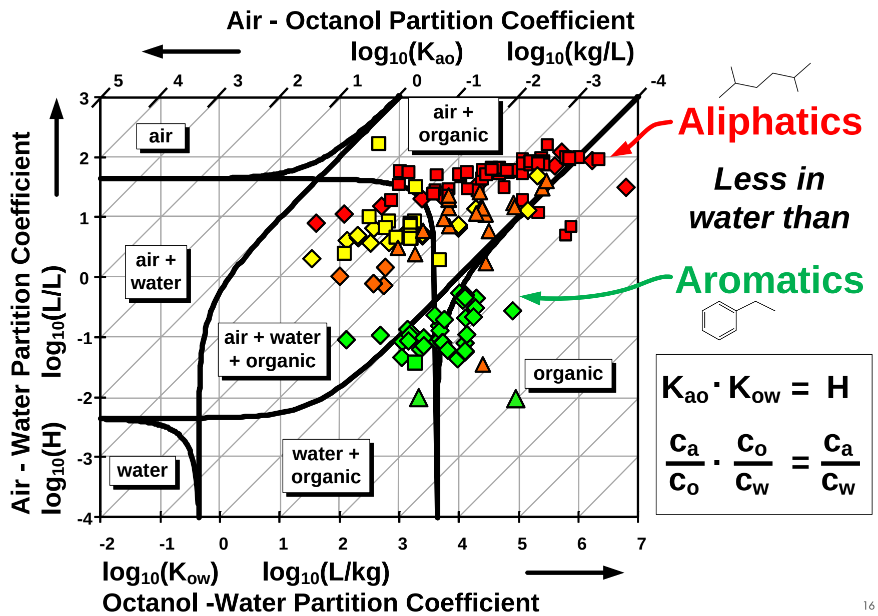
Petroleum Chemical Phase Partitioning in Soil



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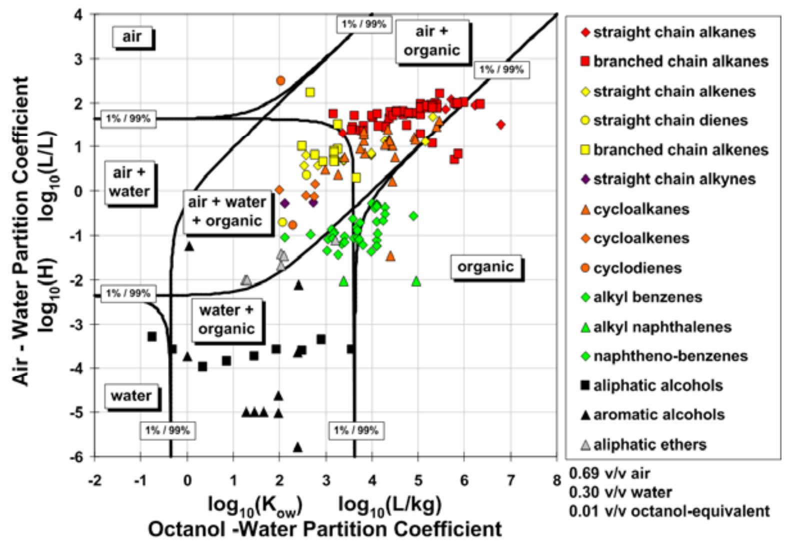
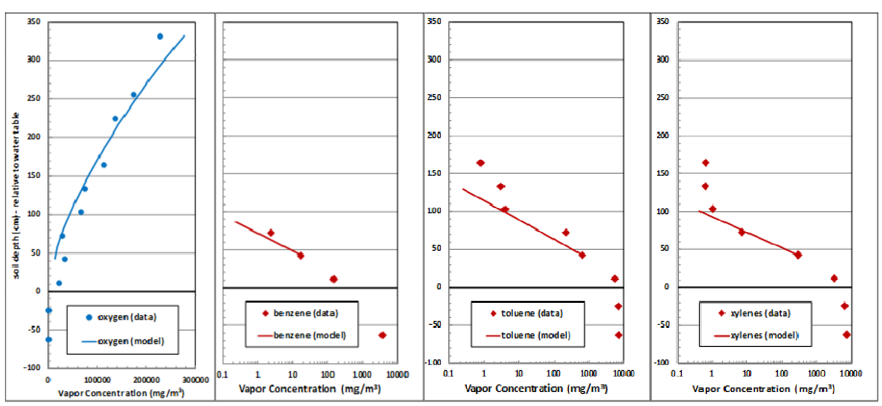
... and alcohols



Beaufort, South Carolina

- Measured data to BioVapor Model comparison (using these rates)
  - Favorable comparison of petroleum & oxygen concentrations



Data: Lahvis et al., *Water Resources Research*, 1999, 35, 3, 753-765.

Basics – Introduction - PVI

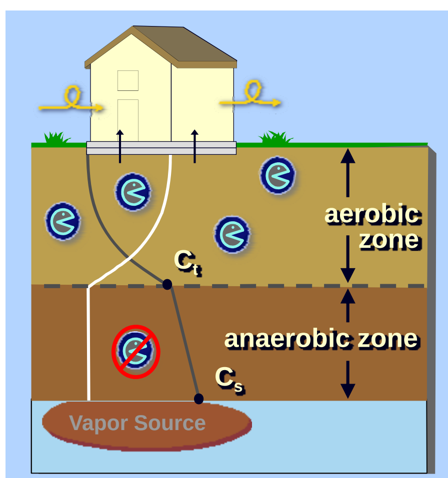
To Be Covered:

- Conceptual Models
- Biodegradation
- Building Foundations and Oxygen

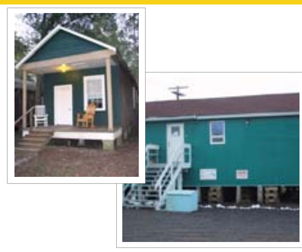
Oxygen Under Building Foundation

Key Question:

- Is there enough oxygen below building foundations to support aerobic biodegradation?



Building Foundation Types and Air Flow



"Open / breezy" foundation: high airflow

- Raised buildings: on stilts, piles, piers:
  - Due to unstable soils, wet soils (expansive clays, muskeg, bogs, swamps) or climate (air circulation, termites, flooding).

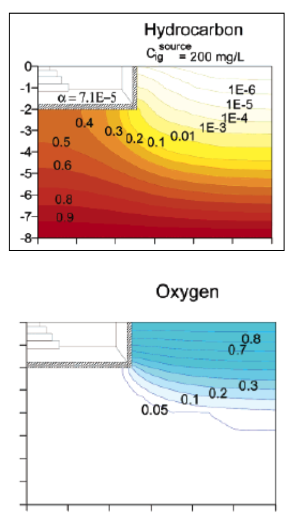
"Airtight" Foundations - limited airflow:

- Slab-on-grade. Basements.
- Crawlspaces.
  - Edge walls depth: frost heave
  - Influenced by capillary break or vapor barriers [moisture control]

Buildings may be "airtight" or "open / breezy" depending on soils.
Suggestion: If unknown, choose nominal "worst case" for the area.

Oxygen Under Foundation: Model Prediction

- Numerical model predicts oxygen shadow below building, but.....
- Very strong vapor source (200,000,000 ug/m^3)
- All flow into building is through perimeter crack
- No advective flow directly below building



KEY POINT:	**This model does not account for key oxygen transport processes.**

From Abreu and Johnson, ES&T, 2006, Vol. 40, pp 2304 to 2315

Aerobic Biodegradation: Mass Balance

Hydrocarbon + Oxygen $\xrightarrow{\text{microbes}}$ Carbon Dioxide + Water

$$1\ \text{kg}\ C_xH_y + 3\ \text{kg}\ O_2 \longrightarrow 3.4\ \text{kg}\ CO_2 + 0.7\ \text{kg}\ H_2O$$

- 21% oxygen (= 275 g/m^3)
- Provides capacity to degrade 92 g/m^3 hydrocarbon vapors

KEY POINT: Even limited migration of oxygen into subsurface will support significant aerobic biodegradation.

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Transport of Oxygen Under Foundation

- **Wind Driven Advection**
  - lateral pressure upwind / downwind
- **Bi-Directional Pressure Flow Across Foundation (back and forth)**
  - Time-dependent pressure fluctuations
  - Indoor VOCs detected in sub-slab samples (McHugh)
- **Indoor-Subsurface Pressure gradient (steady)**
  - Mean flow volume balance (out = in)
- **Oxygen Diffusion through Concrete (Large Area)**
  - Measured diffusion rates are not zero

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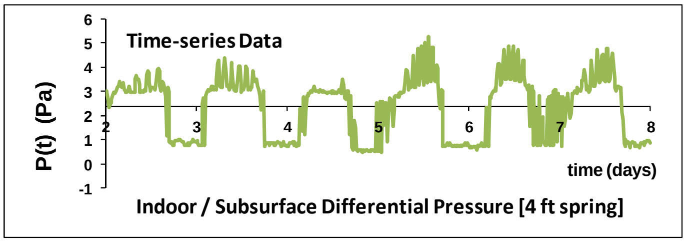
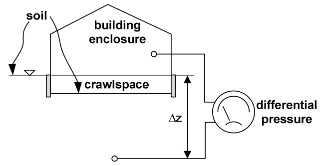
time-dependent pressure

- Back-and-forth:
  - air flow follows pressure gradient



- warm days and cold nights
  - Induced: Furnace cycling
  - Direct: Temperature differences, wind
- Varies with building & season



Oxygen Blow Buildings

- Summary:
- Even modest oxygen transport yields sufficient aerobic biodegradation in most cases
- Oxygen demand (from high hydrocarbon source) can deplete oxygen below building foundations and capping layers.
- Very Large Buildings ?
  - Refinery site: Perth, Australia (Patterson and Davis, 2009)
  - Measured Depleted Oxygen below Building Center
  - 35 to 40 g/m^3 hydrocarbon vapor above LNAPL at 10 feet depth

Two key factors – both needed:

1. Limited oxygen transport below the foundation &
2. High oxygen demand

Conclusion: Introduction Overview

Subsurface source to indoor air vapor intrusion

Actual Issues: Petroleum VI

- **Occur very infrequently**
- **Occur (sometimes) with:**
  - **Very large releases of petroleum to the subsurface**
  - **Petroleum LNAPL very close, in contact with, or inside a basement or utility connected to an enclosure**

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Workshop Agenda

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- Evaluating the Vapor Intrusion Pathway - Studies *45 minutes*
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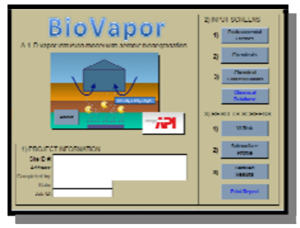
BioVapor Model

To Be Covered:

- **Model Introduction**
- **Application Examples**



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J&E Model: Subsurface Vapors to Indoor Air Vapor Intrusion

- Johnson and Ettinger (1991): Heuristic model for predicting the intrusion rate of contaminant vapors into buildings, Environ. Sci. Tech., 25:1445-1452.
  - Applied: ASTM E2081-00; E1739-95; USEPA, 2003; others
- USEPA OSWER - Subsurface Vapor Intrusion Guidance (2002):
  - "The draft guidance recommends certain conservative assumptions that may not be appropriate at a majority of the current 145,000 petroleum releases from USTs. As such, the draft guidance is unlikely to provide an appropriate mechanism for screening the vapor pathway at UST sites."
- Tillman, F.D. and J.W. Weaver, 2005, Review of recent research on vapor intrusion, EPA/600/R-05/106
  - "While caution would require the evaluation of the soil-to-indoor air pathway for all subsurface contamination, there are, in fact, not many cases of proven vapor intrusion documented in the scientific literature. This is particularly true for organic vapors subject to aerobic biodegradation, such as gasoline compounds (petroleum hydrocarbons).

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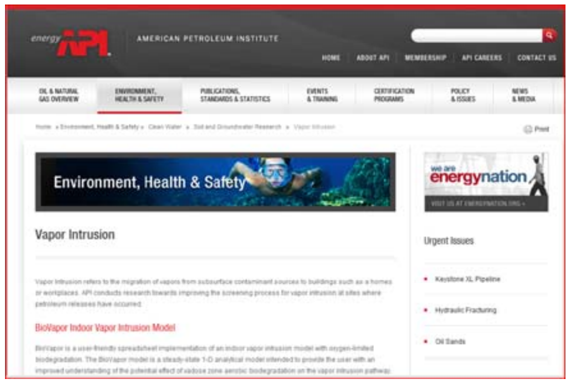
American Petroleum Institute BioVapor Model

Download at: www.api.org/pvi
OR Navigate www.api.org to
Environment, Health & Safety > Soil & Groundwater Research > Vapor Intrusion
Free, asks for registration information (update notification)



Questions (API): Roger Claff, claff@api.org, 202-682-8399;
Bruce Bauman, Bauman@api.org, 202-686-8345
Acknowledgements: Tom McHugh, Paul Newberry,
GSI Environmental, Houston.

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BioVapor: Intended Application

yes

- Improved understanding of Petroleum Vapor Intrusion
- Calculate oxygen concentration / flux required to support aerobic biodegradation
- Identify important model input parameters and output variables – and their sensitivity
- Available, free

no

- Predict hydrocarbon concentrations in indoor air within a factor of 10
  - Site complexity
  - Temporal variability
  - Indoor background

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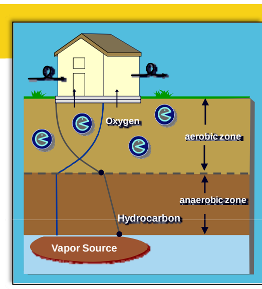
Model Use Comparison

Many models are available … tradeoffs

- **Complex**: numerical, multi-dimensions, time-dependent
  - intensive computation, potentially few users
  - Explore building / foundation interaction details
  - Lateral building / foundation to source separation
  - Can be 'stiff' (numerically unstable)
- **Simple**: analytical, semi-analytical, one-dimension
  - Very fast calculations
  - Multiple chemicals, oxygen sinks, no problem
  - Sensitivity estimates are realistically possible
  - Insight into trends, sensitivity, key parameters
  - Easily coded and run

Yao and Suuberg, 2013: A Review of Vapor Intrusion Models, ES&T

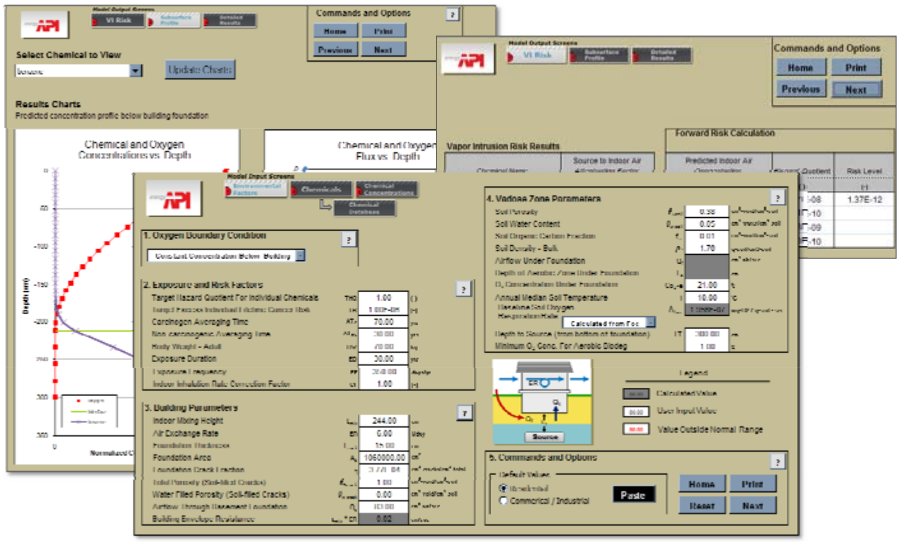
API BioVapor: Use



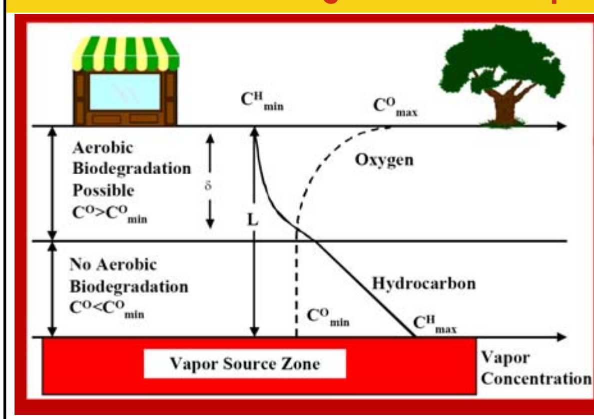
- **Structure**
  - **Menu-driven**
  - **Microsoft Excel™ spreadsheet**
    - **Open, unlocked, reference guidance**
- **Input:**
  - **Same or similar parameters as Johnson & Ettinger model**
    - **Similar conceptual model & caveats on model applicability and use.**
    - **Includes 'oxygen-limited aerobic biodegradation' (DeVaull, ES&T 2007)**
  - **Additional Parameters and Information**
    - **Either can be readily estimated, or**
    - **Included in database (example: chemical-specific aerobic degradation rates)**

Key:
- **Quantify the contribution of aerobic biodegradation**
- **Available and relatively easy to use**

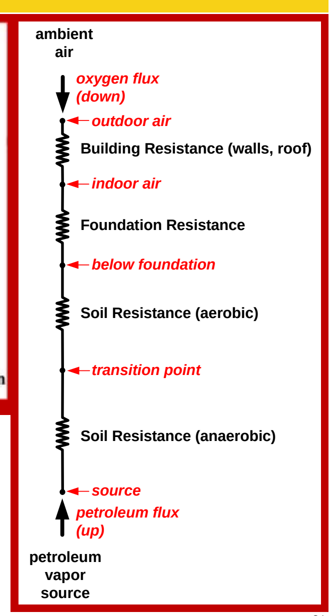
BioVapor: Menus & output



Petroleum Biodegradation Conceptual Model



Key Idea: oxygen consumption and hydrocarbon attenuation are directly correlated



Oxygen below Buildings: Basis

- Aerobic Biodegradation
  - Hydrocarbon to Oxygen use ratio: 1 : 3 (kg/kg)
  - Atmospheric air (21% Oxygen; 275 g/m^3 oxygen) provides the capacity to degrade 92 g/m^3 hydrocarbon vapors (92,000,000 ug/m^3)
- Oxygen below a Foundation: can it get there?
  - Through the foundation
    - Equate to same transport parameters as other VI chemicals
  - Around the foundation edges (bonus)
    - Additional oxygen

Key: Oxygen below a foundation
- Can oxygen get there?
- Is there enough oxygen to support significant aerobic biodegradation?

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Oxygen in the BioVapor Model

- Three Options:
  1. Specify Aerobic depth
     - Measure vapor profile
  2. Specify Oxygen concentration under a foundation
     - Measure oxygen
  3. Let the model balance hydrocarbon & oxygen consumption
     - Specify vapor source composition (gasoline vapor, etc.)
     - Estimate or measure hydrocarbon source

Key:
- Pick one method; the others are related (and predicted)
- Relatively unique to this model (particularly #3)

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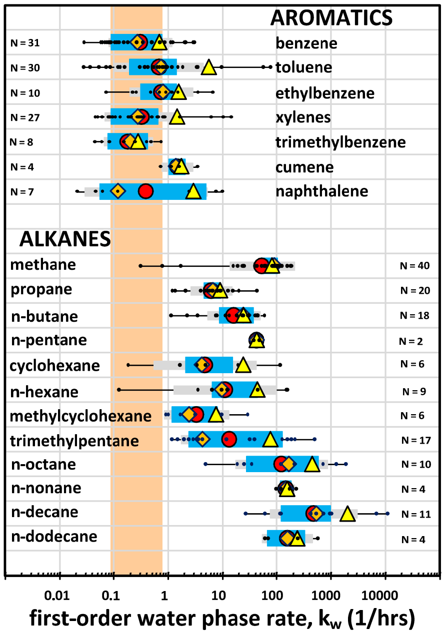
Aerobic Petroleum Biodegradation Rates in Soil



Aromatic Hydrocarbons

k_w = 0.48 /hr (0.08 to 3.0)

k_w = 40 /hr (7.8 to 205)

Aliphatic Hydrocarbons

geometric mean • data values
median arithmetic mean
data ranges: 50%, 68% (2 σ_g), 100%

- **Chemical-Specific Rates**

DeVaull, 2011: *Biodegradation rates for petroleum hydrocarbons in aerobic soils: A summary of measured data*, International Symposium on Bioremediation and Sustainable Environ. Technol., June 2011, Reno.

'reaction length' $L_R = \sqrt{\dfrac{D_{eff} \cdot H_i}{\theta_w \cdot k_w}}$

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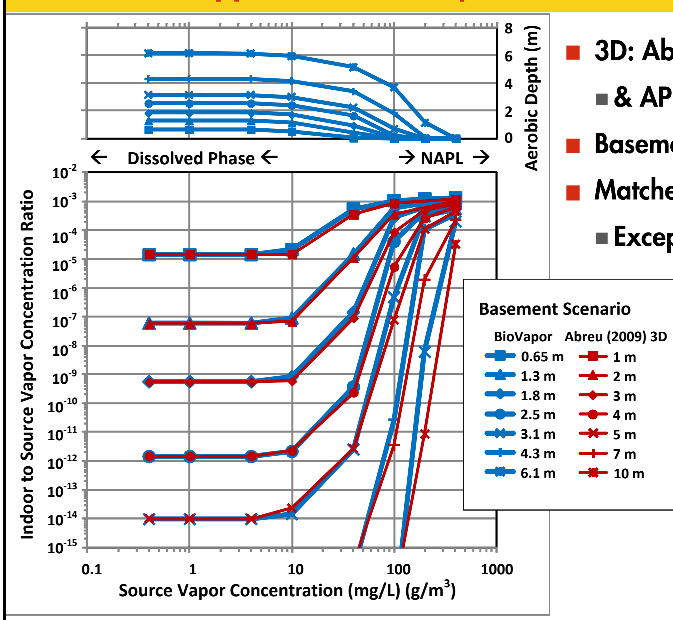
Model Application 1: Compare 1-D to 3-D Estimates

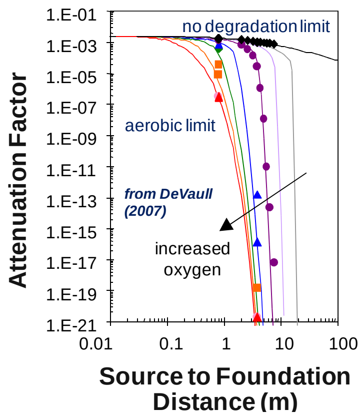


- **3D: Abreu 2009: GWM&R**
  - **& API Publ. 4555**
- **Basement Scenario**
- **Matched Parameters**
  - **Except "Depth"**

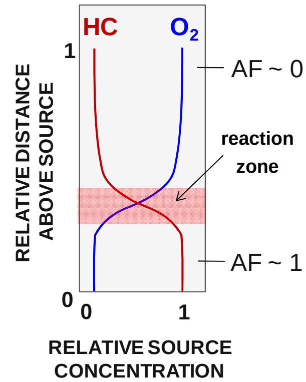
Model Application 1: Compare 1-D to 3-D Estimates

- 3-D (Abreu) and 1-D (BioVapor) model
  - **Matched scenarios, oxygen demand & availability, chemical kinetics**
  - DeVaull, 2007: A&WMA VI Conference, Providence, RI.
- Both models show a distance beyond which indoor impacts are virtually negligible

Comparison of BioVapor model to Abreu and Johnson (2006) 3-D numerical model results

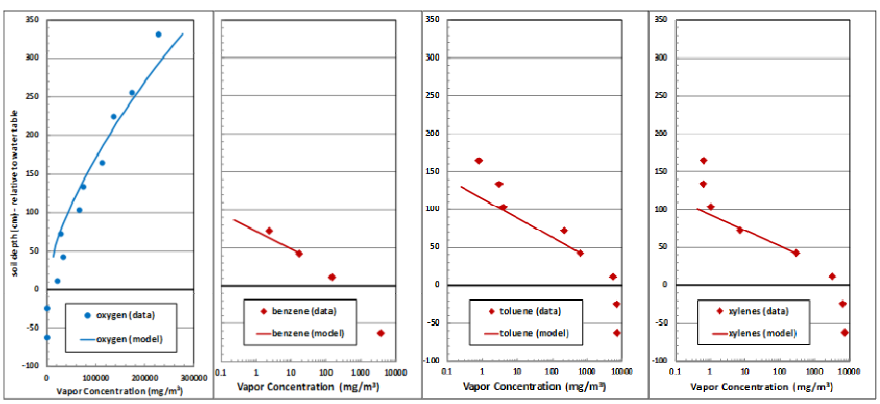


Conceptual Behavior



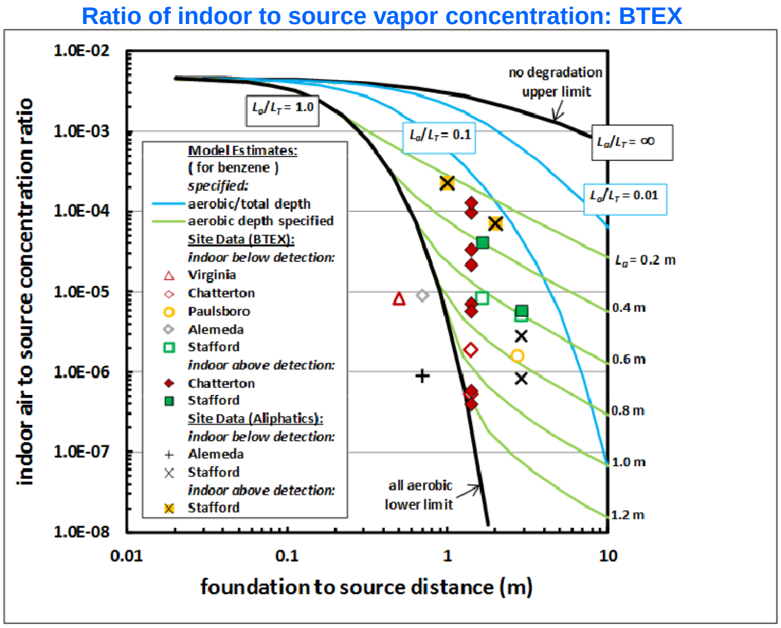
Application 2 – Measured Data to BioVapor Comparison

- Beaufort, South Carolina
  - **Favorable comparison of petroleum & oxygen concentrations**



Data: Lahvis et al., *Water Resources Research*, 1999, 35, 3, 753-765.

Application 2 – Measured Data to BioVapor Comparison



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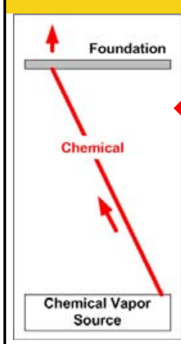
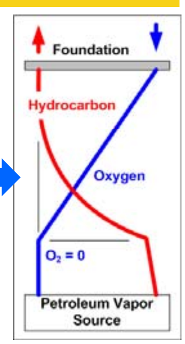
Model Application 3: Extreme Conditions

Potential "worst case" indoor air concentrations

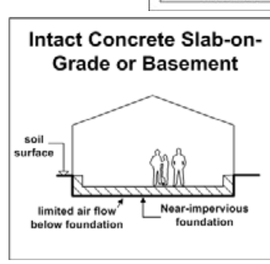


Building Foundation Types:

- Non-degrading chemicals:
  - High Vapor Flow Through Foundation
- Aerobically degrading petroleum:
  - Low Oxygen (Air) Flow through Foundation



Key Ideas: "Worst Case" Conditions
- Same for or Building, Soils and Vapor Source
- Opposite Extreme for Foundation Type



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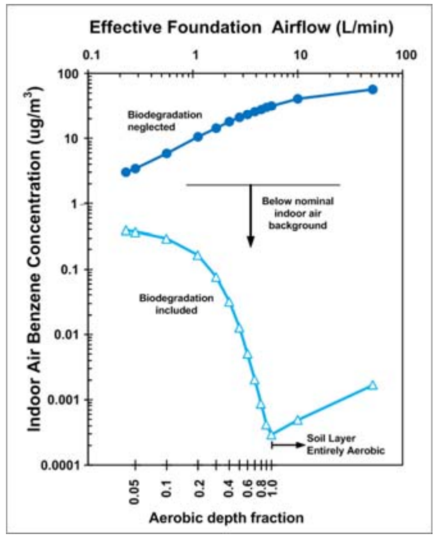
Model Application 4: Sensitivity Analysis

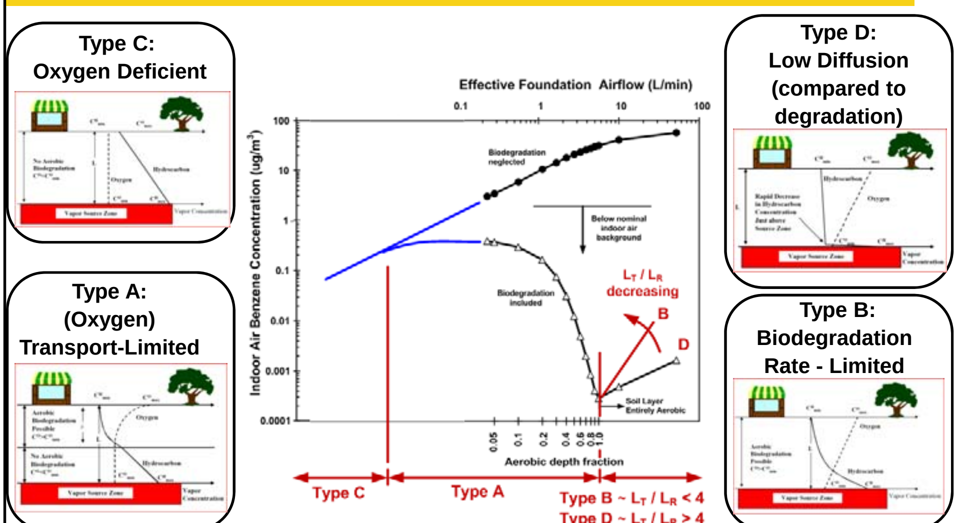
Is a proposed exclusion distance okay for varied buildings?

- **Base Case 'Exclusion Distance':**
  - 5 ft separation, water-dissolved source
  - 1 mg/L benzene, 10 mg/L BTEX
  - Robin Davis (2010)
- **Without Biodegradation**
  - Higher foundation airflow,
  - Higher indoor air concentration
- **With Aerobic Biodegradation**
  - Higher foundation airflow,
  - Lower indoor air concentration
  - (if oxygen limited)



Model Estimates (BioVapor, www.api.org/vi)
Residential default parameters, varied foundation airflow

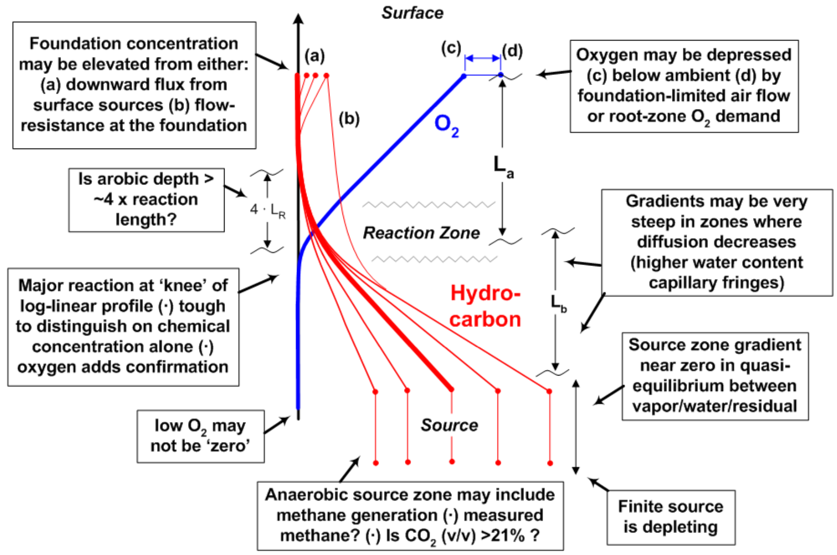
Model Application 4A: Scenario Type Classification



Profile Type Classes from: Roggemans, et al., 2001: API Soil and Groundwater Research Bulletin No. 15.

Soil Gas Profile Interpretations

Biodegradation Model helps classify ranges of behavior:



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Sensitivity Analysis 1:

BioVapor User's Guide:

- "Some required or optional model inputs parameters such as oxygen concentration below the building foundation and baseline soil oxygen respiration rate are not commonly measured during site investigation. **…the user should conduct a sensitivity analysis in order to evaluate the effect of input parameter value uncertainty on the model results**"
- "Users of this model should not rely exclusively on the information contained in this document. Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein."
- Neither API nor any….

Weaver, J. (2012). BioVapor Model Evaluation, For 23rd National Tanks Conference Workshop St. Louis, Missouri, March 18, 2012

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Sensitivity Analysis 2:

BioVapor versus Johnson and Ettinger:

- Parameter importance ranking
  - Primary
    - Depth, source concentration
    - Oxygen content, biodegradation rate, foundation air flow, soil moisture content
  - Secondary
    - Air exchange rate, other factors in J&E
  - Results will be more strongly dependent on source depth and strength than analogous J&E, and unless the source is right below foundation, less dependent on building parameters.

Weaver, J. (2012). BioVapor Model Evaluation, For 23rd National Tanks Conference Workshop St. Louis, Missouri, March 18, 2012.
Picone, S. et al., 2012: Environmental Toxicology and Chemistry, Vol. 31, No. 5, pp. 1042–1052, 2012.

BioVapor Model: Forward Plan

- Use:
  - Improved Understanding, Oxygen Requirements, Sensitivity
    - Baseline Site Screening, Sample Plan Development, Training
    - What-if Analysis (foundation / no foundation, etc.)
    - It is .. a model
- Review and Plans:
  - Validation and sensitivity analysis (EPA OUST, ORD)
  - EPA: recoding
  - API Workshop: Interactive Demonstration / Case Studies
  - Fixes and Updates: Very Few 'Bugs' or Model Issues to Date

American Petroleum Institute BioVapor Model

Download at: www.api.org/pvi
OR Navigate www.api.org to
Environment, Health & Safety > Soil & Groundwater Research > Vapor Intrusion
Free, asks for registration information (update notification)

Questions (API): Roger Claff, claff@api.org, 202-682-8399;
Bruce Bauman, Bauman@api.org, 202-686-8345
Acknowledgements: Tom McHugh, Paul Newberry,
GSI Environmental, Houston.

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Workshop Agenda

- Welcome, Introductions, Safety Issues
- Update on ITRC VI Workgroup
- Update on EPA OUST
- PVI Overview; BioVapor and other models; and **Introduction to Exclusion Criteria**
- Evaluating the Vapor Intrusion Pathway - Studies *45 minutes*
- Regulatory updates effecting sampling and Analysis
- Case Studies/ Lessons
- Summary

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State Summary

- 35 States with Vapor Intrusion Guidance

Screening Values:

media	values	range
indoor air	0.084 to 4.98 ug/m^3	140x
groundwater	2.4 to 3500 ug/L	1500x
shallow soil gas	3.1 to 190,000 ug/m^3	61,000x

Clearly, a lot of variability

Eklund, B., L. Beckley, V. Yates, T. E. McHugh, Overview of State Approaches to Vapor Intrusion, Remediation, Autumn 2012, 7-20.

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Petroleum Hydrocarbons And Chlorinated Hydrocarbons Differ In Their Potential For Vapor Intrusion

USEPA OUST 2011http://epa.gov/OUST/cat/pvi/index.htm

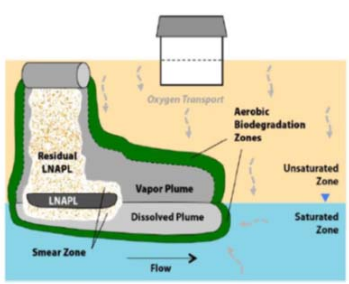

Figure 1. Typical petroleum hydrocarbon transport conceptual scenario

Aerobic biodegradation of PHCs along the perimeter of the vapor and dissolved plumes limits subsurface contaminant spreading. Effective oxygen transport (dashed arrows) maintains aerobic conditions in the biodegradation zone. Petroleum LNAPL (light nonaqueous phase liquid) collects at the groundwater surface (the water table, blue triangle).

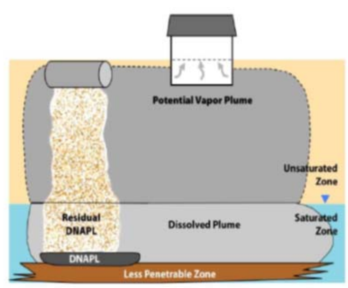

Figure 2. Typical chlorinated solvent transport conceptual scenario

Biodegradation of CHCs is anaerobic and usually slower than PHC biodegradation, so that the vapor and dissolved plumes often migrate farther than PHC plumes. CHC DNAPL (dense nonaqueous-phase liquid), if present, can sink below the water table, collecting in this case on a less penetrable layer.

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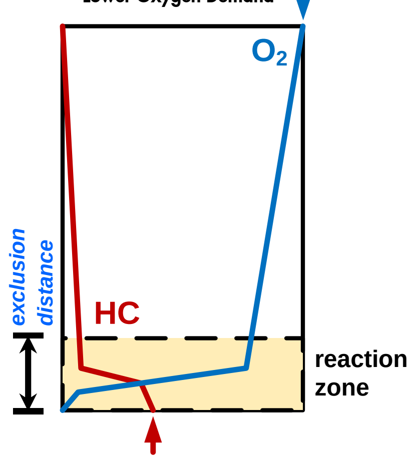
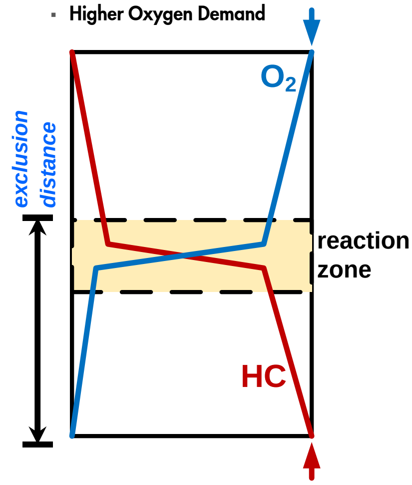
Scenario Type Classification

- Lower Concentration Source
  - Dissolved Groundwater Source
  - Clean Soil Model
  - Lower VOC flux
  - Lower Oxygen Demand
- Higher Concentration Source
  - LNAPL Source
  - Dirty Soil Model
  - Higher VOC Flux
  - Higher Oxygen Demand





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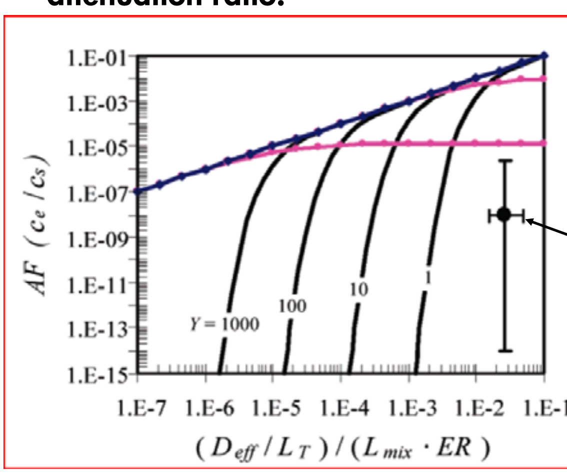
Exclusion Distances

- Distance is a much more robust screening factor than an attenuation ratio.



Increase separation distance by a factor of 2, attenuation factor decreases by a factor of 8E-06

DeVaull, G. E., *Environ. Sci. Technol.* **2007**, *41*, 3241-3248.

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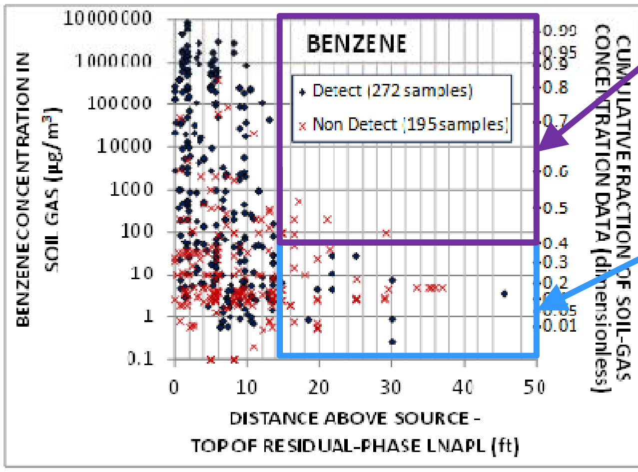
Exclusion distance

- Scatter plot – soil gas vs. distance from water table



No detects at all in this quadrant

Low % detect & conc. in this quadrant

Lahvis, M.A., et al., Vapor Intrusion Screening at Petroleum UST Sites, *Groundwater Monitoring and Remediation* [Article first published online: 21 Feb 2013].

Petroleum Vapor Exclusion Distances

- 23 states - Range: 5 ft to 100 ft – dissolved phase.
  - Eklund, et al. 2012
- Site Vapor Database review:
  - Dissolved : 0 feet; 5 ft;
  - LNAPL: 15 ft
  - Lahvis et al., GWMR, online: 21 Feb 2013.
- Proposed:
  - LNAPL : 15 to 30 feet
  - Dissolved phase : somewhat less
  - Added factors of conservatism: ???

Petroleum Vapor Intrusion

- USEPA OUST PVI Guidance
  - Exclusion distances
  - Biodegradation – Modeling
- USEPA OSWER VI Guidance
  - Not USTs

- Each scheduled Nov 2012
  - Not too far off …

End

- End