REUSE IN RHODE ISLAND
A State-Based Approach To Complex Exposures

BROWN

Vapor Intrusion: Environmental Health Risks, Technical and Regulatory Challenges

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with acknowledgment of contributions by

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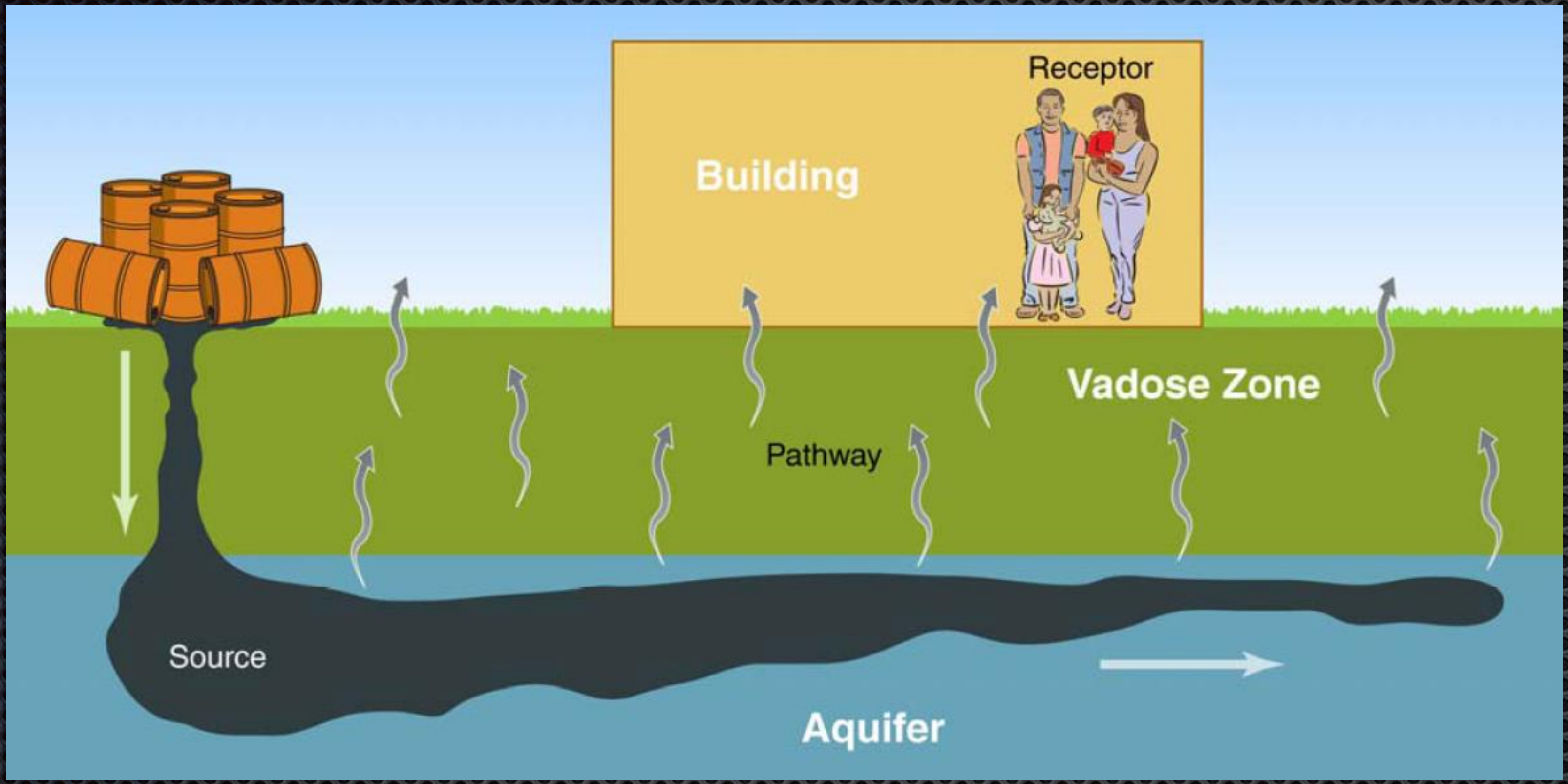
Rhode Island Department of Environmental Management
Northeast Waste Management Officials Association

Srp Superfund Research Program

SRP Annual Meeting, November 13, 2014

Vapor intrusion involves migration of soil contaminants, present as free phase or in groundwater, transporting as vapors through soil, entering buildings through foundation cracks and joints.

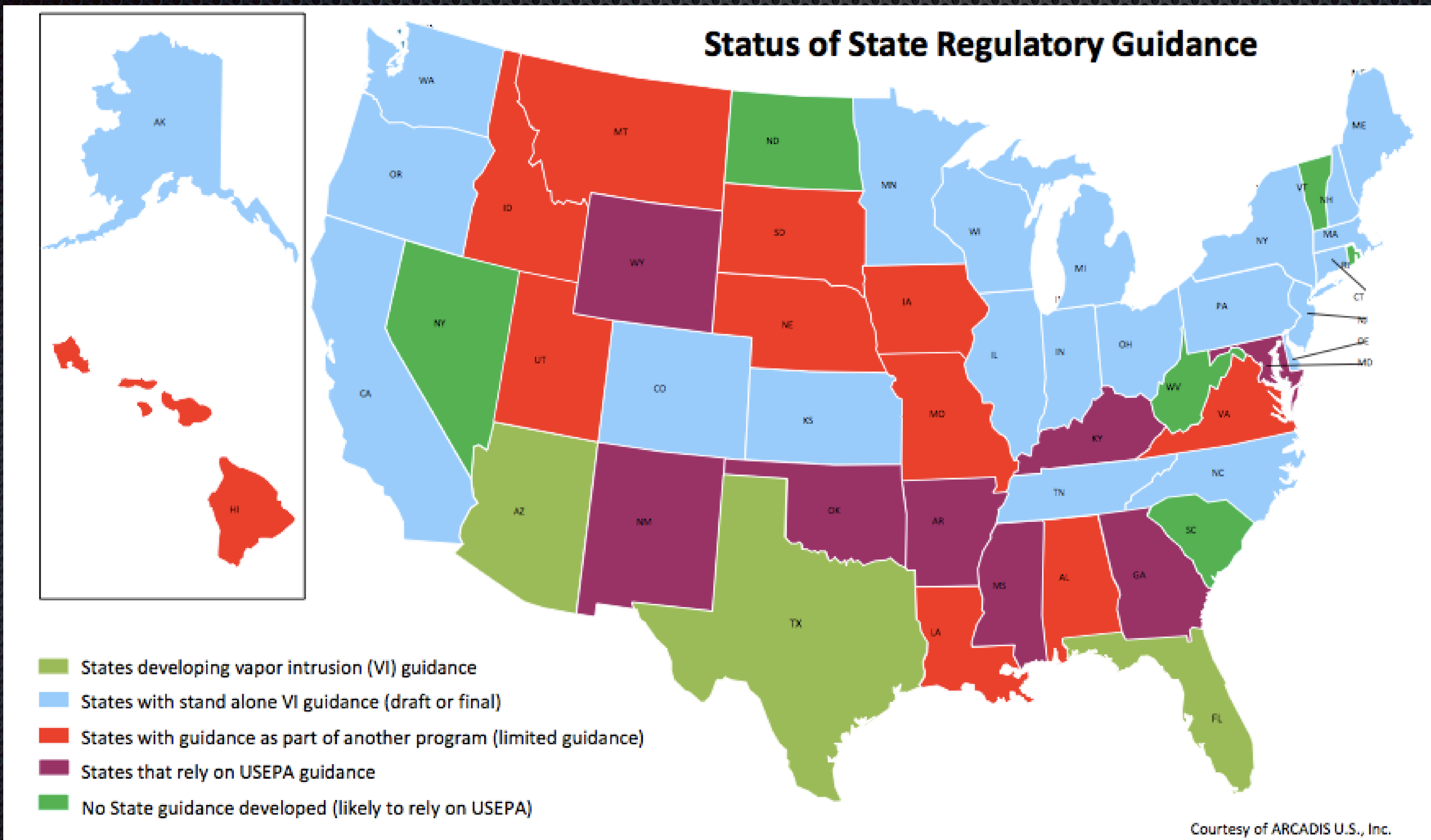


Interstate Technology & Regulatory Council, 2007

A demonstrated health risk must involve a completed exposure pathway, including Source, Migration Route & Receptor- in VI there is a presumption of incomplete pathway. When SAM?

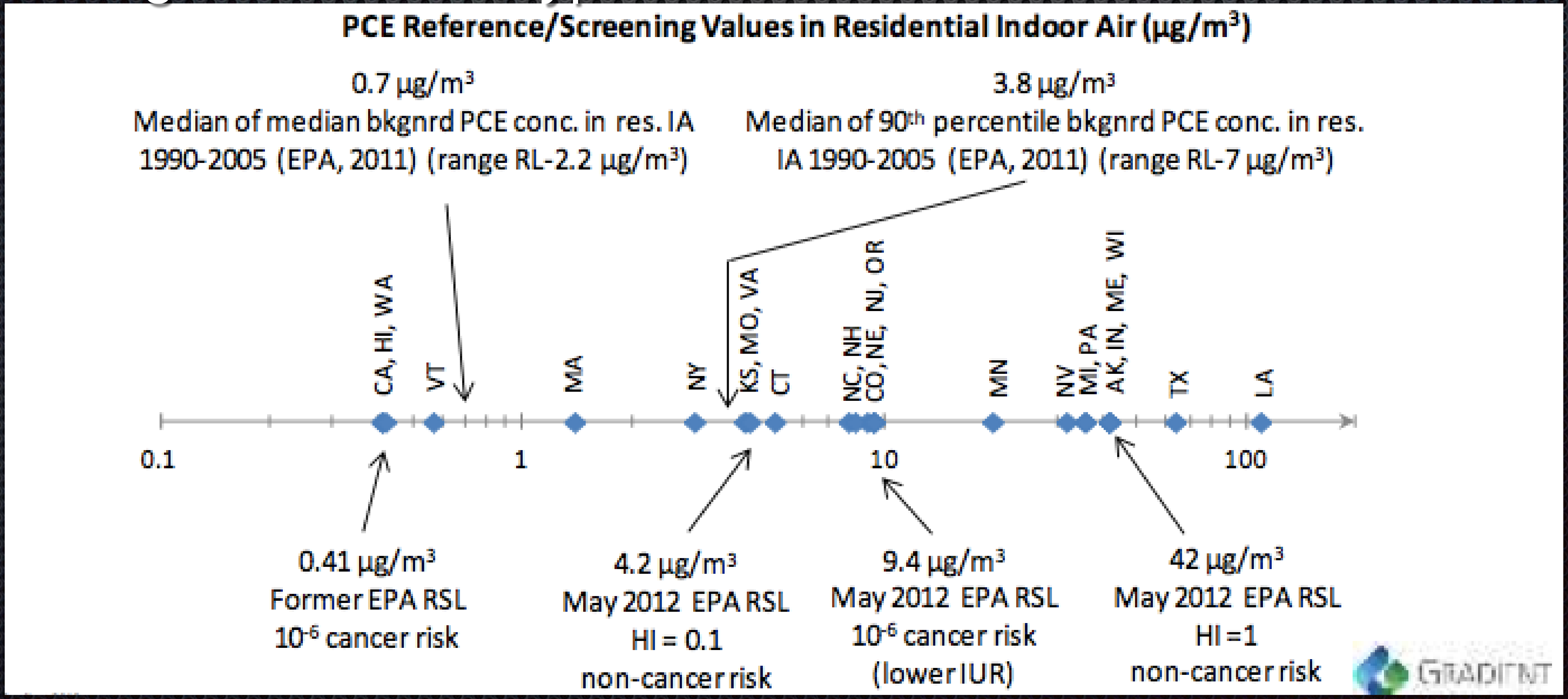
- Affects at least 1/4 of the inventory of 500,000 US brownfields sites (drycleaners-75%?, military bases, petroleum ops.)
- No final EPA guidance
- No agreement on site investigation practices
- Jurisdictional disputes (EPA vs. OSHA)- CERCLA, RCRA, UST, AAI, tort law

A patchwork of regulations



No agreement on screening levels – What is really "safe"?

Many based on cancer risk, e.g. 10^{-5} or 10^{-6}, some on Background levels, typical TO-15 detection limits, some on HI



What is “safe” and which screening value to use?

Table 2. Residential screening levels for selected VOCs.

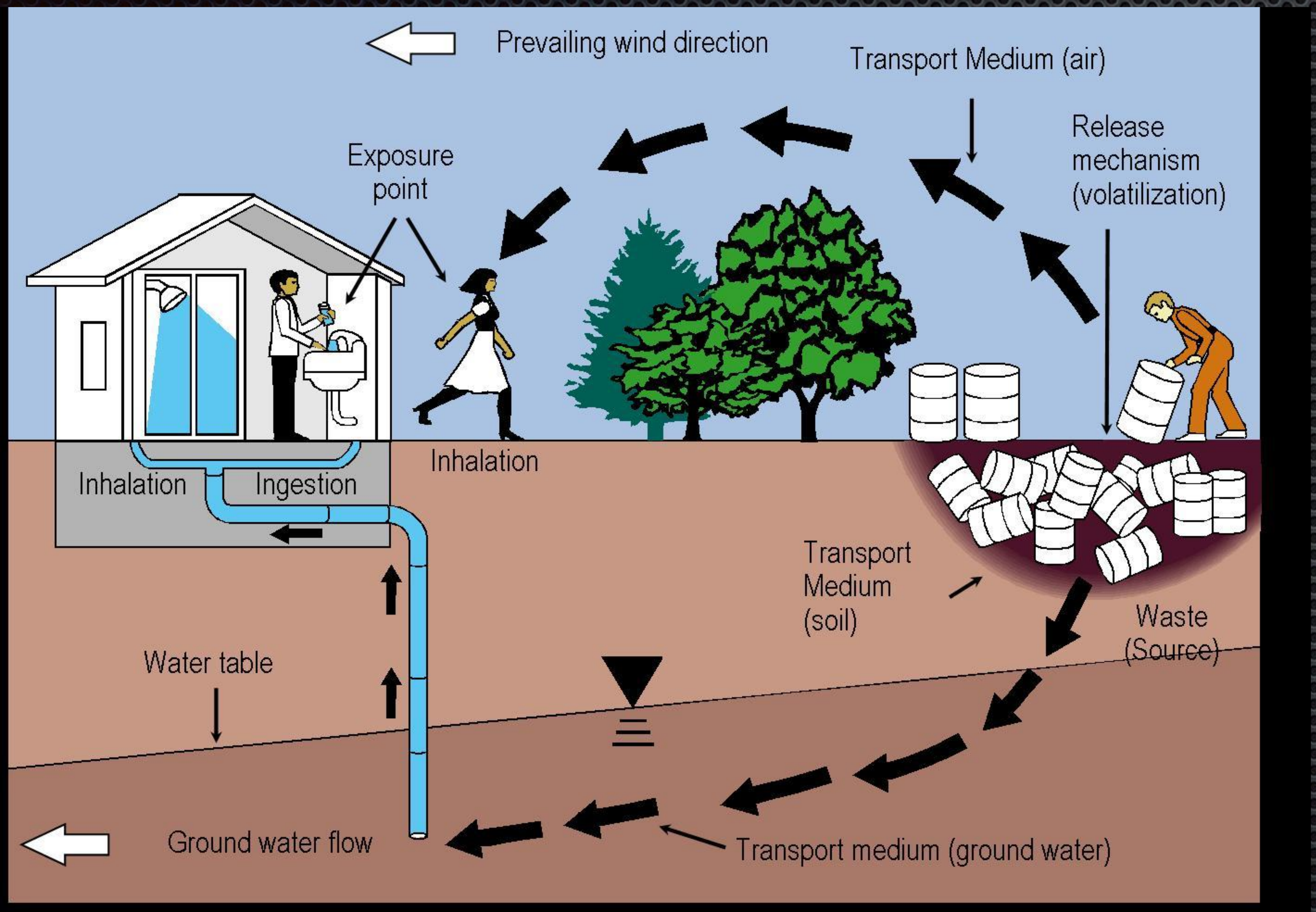
	Benzene			TCE			PCE		
State	**Groundwater**	**Soil Gas**	**Indoor Air**	**Groundwater**	**Soil Gas**	**Indoor Air**	**Groundwater**	**Soil Gas**	**Indoor Air**
Alaska	5	3.1	0.31	5	0.22	0.022	5	8.1	0.81
California	NA	36.2	0.084	NA	528	1.22	NA	180	0.41
Colorado	15	NA	0.23	5	NA	0.016	5	NA	0.31
Connecticut	130	2490	3.3	27	752	1	340	3798	5
Indiana	95-850	250-1400; 25-140[a]	2.5	4.6-700	120-2000; 2-200[a]	1.2-4.1	7.4-1100	320-5200; 32–520[a]	3.2-10
Louisiana	2,900	NA	12	10,000	NA	59	15,000	NA	110
Maine	NA	NA	10[b]	NA	NA	NA	NA	NA	NA
Massachusetts	2000	NA	0.3	30	NA	1.37	50	NA	0.04
Michigan	5600	150	2.9	15,000	700	14	25,000	2100	42
Minnesota	NA	1.3-4.5	1.3-4.5	NA	NA	NA	NA	NA	20
New Hampshire	2000	95	1.9	50	54	1.1	80	68	1.4
New Jersey	15	16	2	1	27	3	1	34	3
New York	NA	NA	NA	NA	NA	5	NA	NA	100
Ohio	14	31	3.1	–	122	12.2	11	81	8.1
Oklahoma	5	3.1	0.27	5	0.17	0.017	5	0.33	0.33
Oregon	160	NA	0.27	6.6	NA	0.018	78	NA	0.34
Pennsylvania	3500	NA	2.7	14,000	NA	12	42,000	NA	36

Notes: Units are μg/L for groundwater and μg/m³ for soil gas and indoor air. See individual state guidance documents for additional information, including limitations and exceptions. Trigger or action levels for mitigation based on indoor air concentrations may be higher than the screening levels shown. [a]Second range of values shown is for subslab soil gas. [b]Chronic exposure value.

From Eklund, Folkes, Kabel, Farnum, in EM, 2007.

The TCE issue has just exploded in the VI field – more controversy on what is "safe"

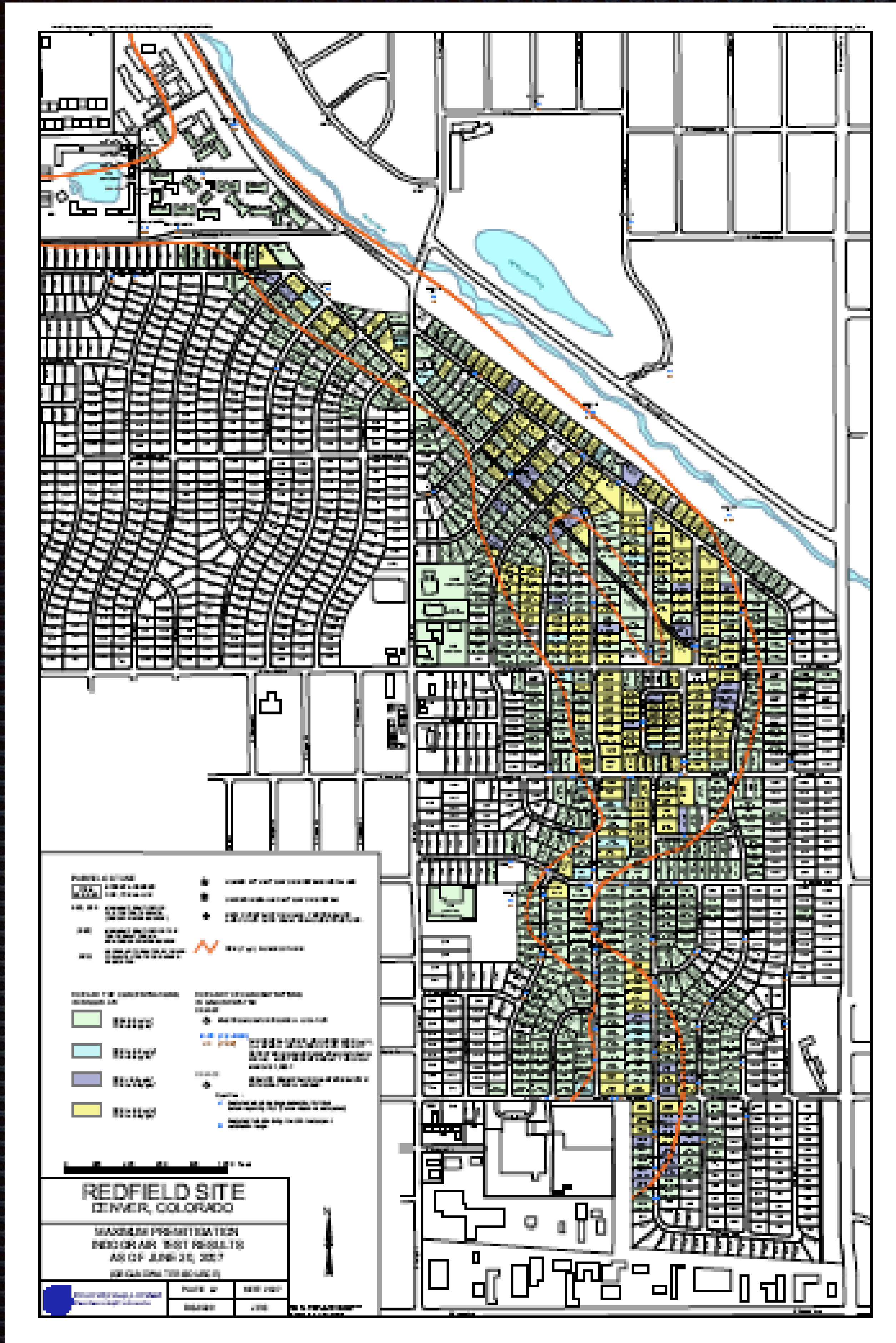
- US EPA IRIS (2011) - RfC=2 µg/m^3, HQ (1) = 2.1µg/m^3, ELCR (10^{-6}) = 0.48 µg/m^3, ELCR (10^{-5}) = 4.8 µg/m^3
- OSHA (PEL- 8 hr) = 537,000 µg/m^3, NIOSH (10 hr) = 134,000 µg/m^3
- Now, risk based indoor air levels are shifting to non-cancer endpoints (e.g. developmental; FCM, thymus weight)
- New "prompt" or "urgent" action levels being based upon RfC- mitigation may be required in weeks or days; may involve temporary relocation. But will the FCM RfC values stand?
- TCE found at 2/3 of Superfund sites



From NEWMOA- "Improving Site Investigation"

Keep in mind- Other exposure routes can come into play (including resident-caused exposures)

Drinking 2 L/day of 5 µg/L (EPA MCL, PCE) results in 10 µg/day dose (and is voluntary), but breathing 20 m^3/day containing 0.5 µg/m^3 exposes individual to same dose and is involuntary.



It is a big problem in many cases.

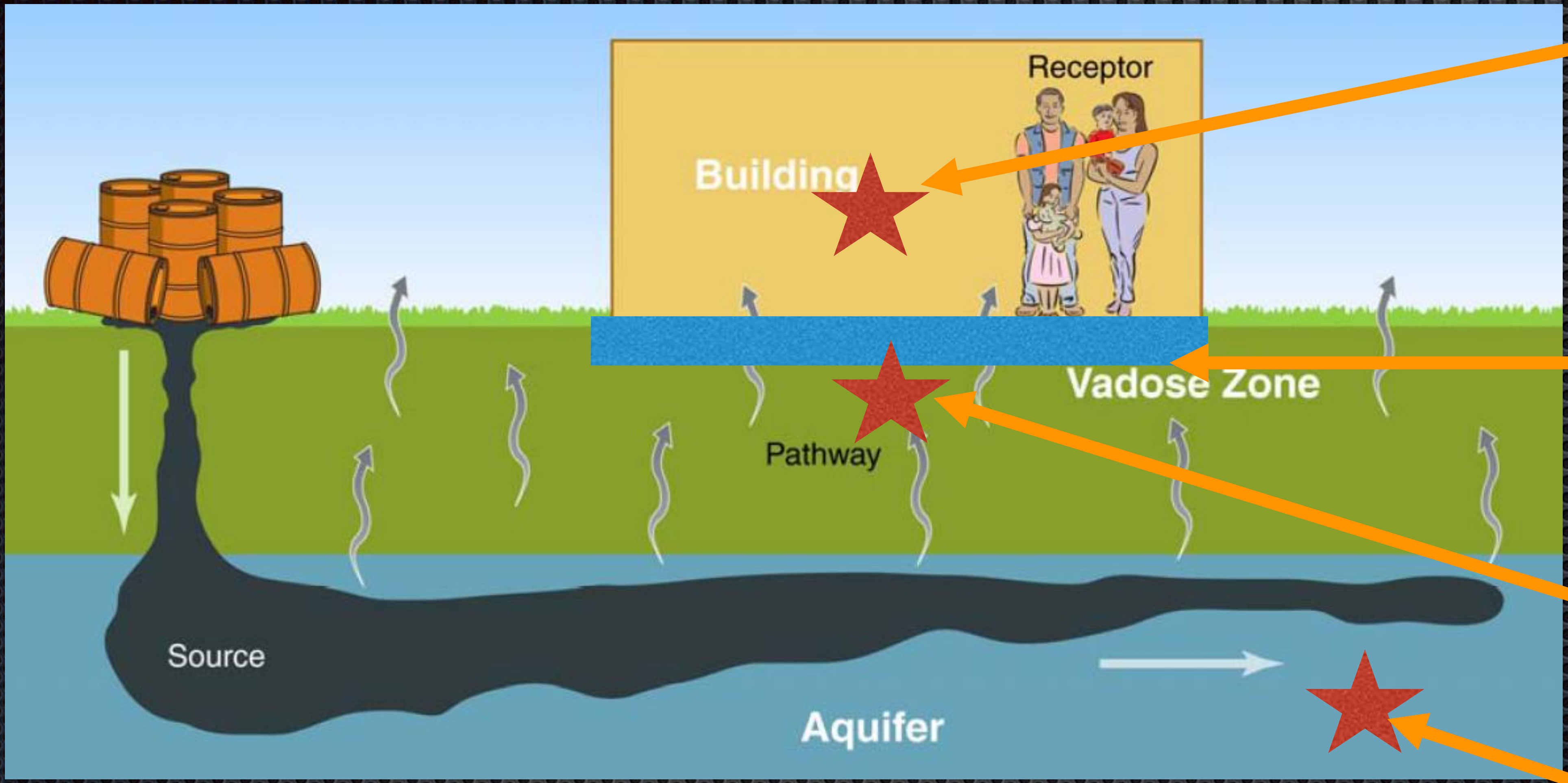
Redfields, CO

Each little rectangle is a home and family....

How can one responsibly evaluate risk to the public?

"I'm from the government, and I'm here to drill a hole in your floor..."
Lenny Siegel CPEO

"Not too long ago consultants and regulators started knocking on the doors of residents in communities such as my home town of Mountain View, California. They wanted to drill holes in the floors. People didn't know what to make of it, but they were scared. Some, fearing the impact of vapor intrusion publicity on property values, wanted to bury their heads in the sand. Cooler heads warned them of elevated levels of cancer-causing substances in the soil gas".



Indoor air sample

Foundation Slab

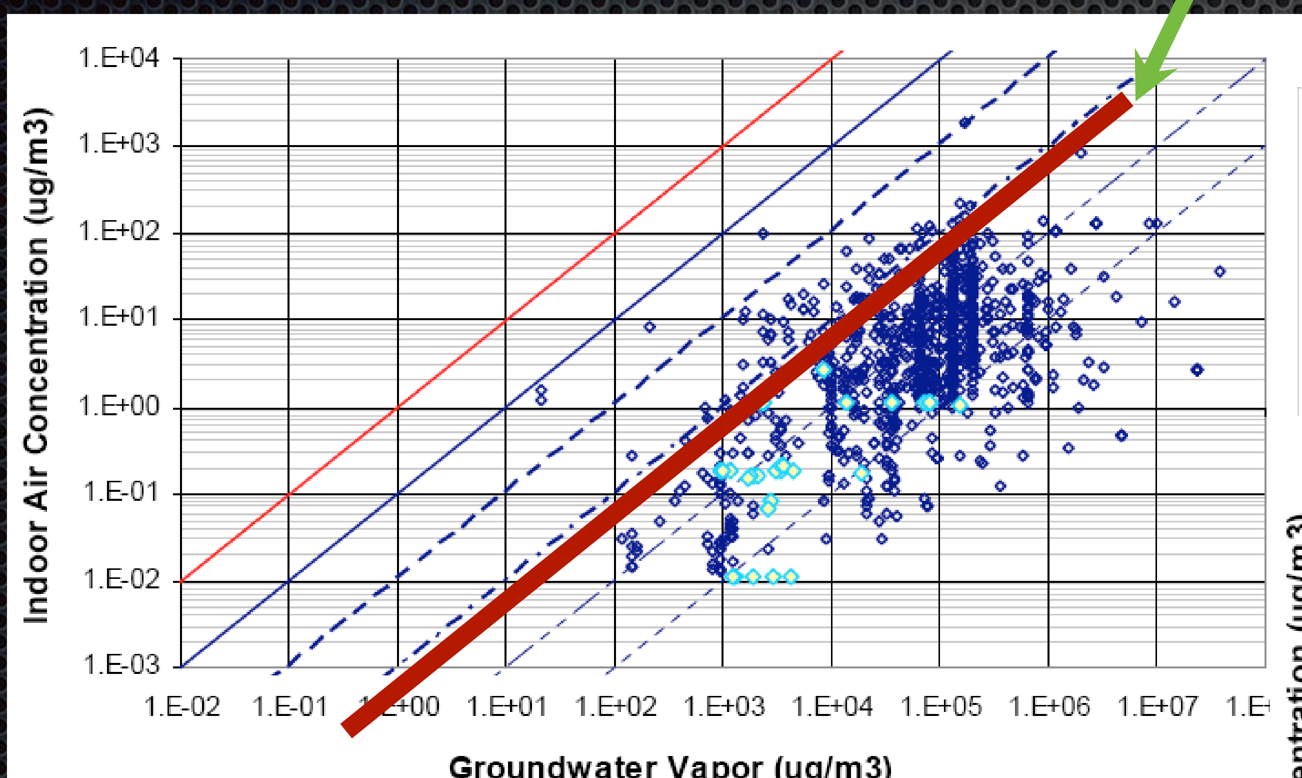
Subslab Soil Vapor Sample Location

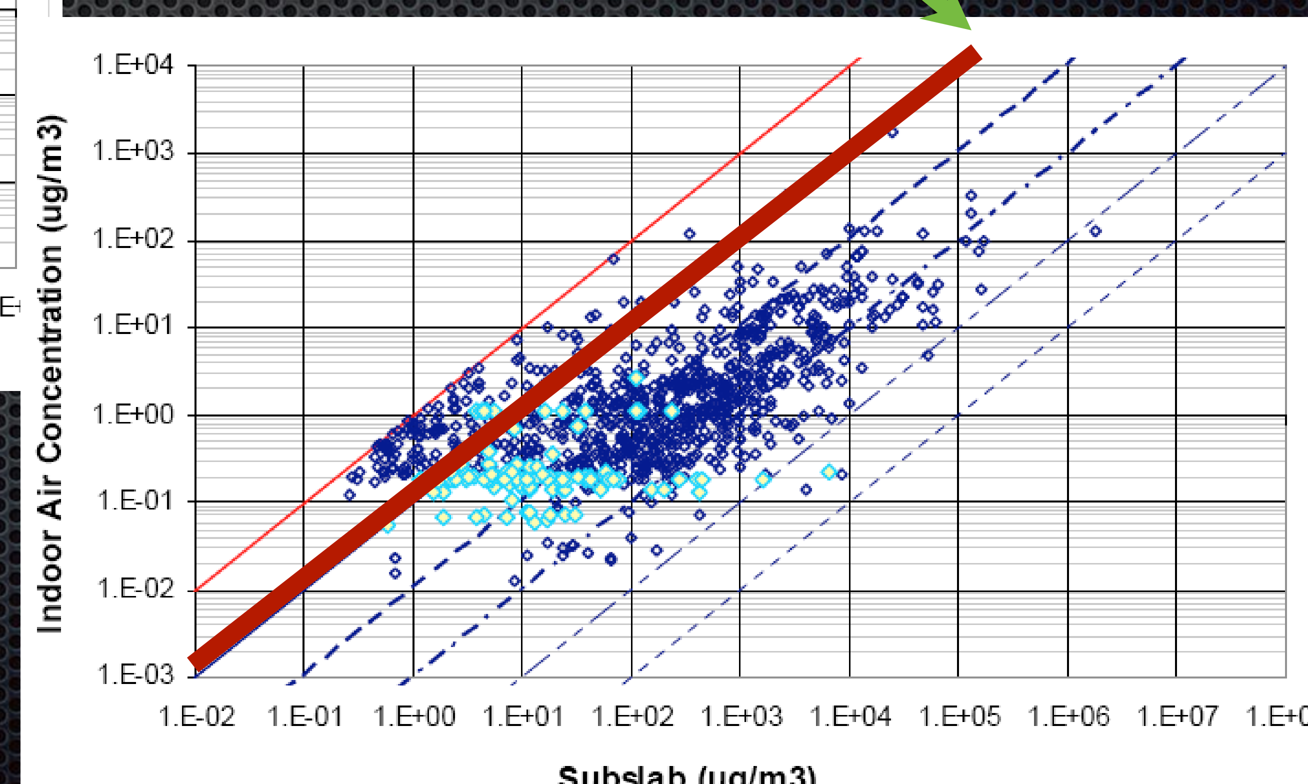
Groundwater sample location (convert to source strength using Henry's Law)

- Screening values- which to use? Levels?
  - Groundwater (Henry's Law), soil gas
  - Subslab, indoor air
- How many samples taken over what time?

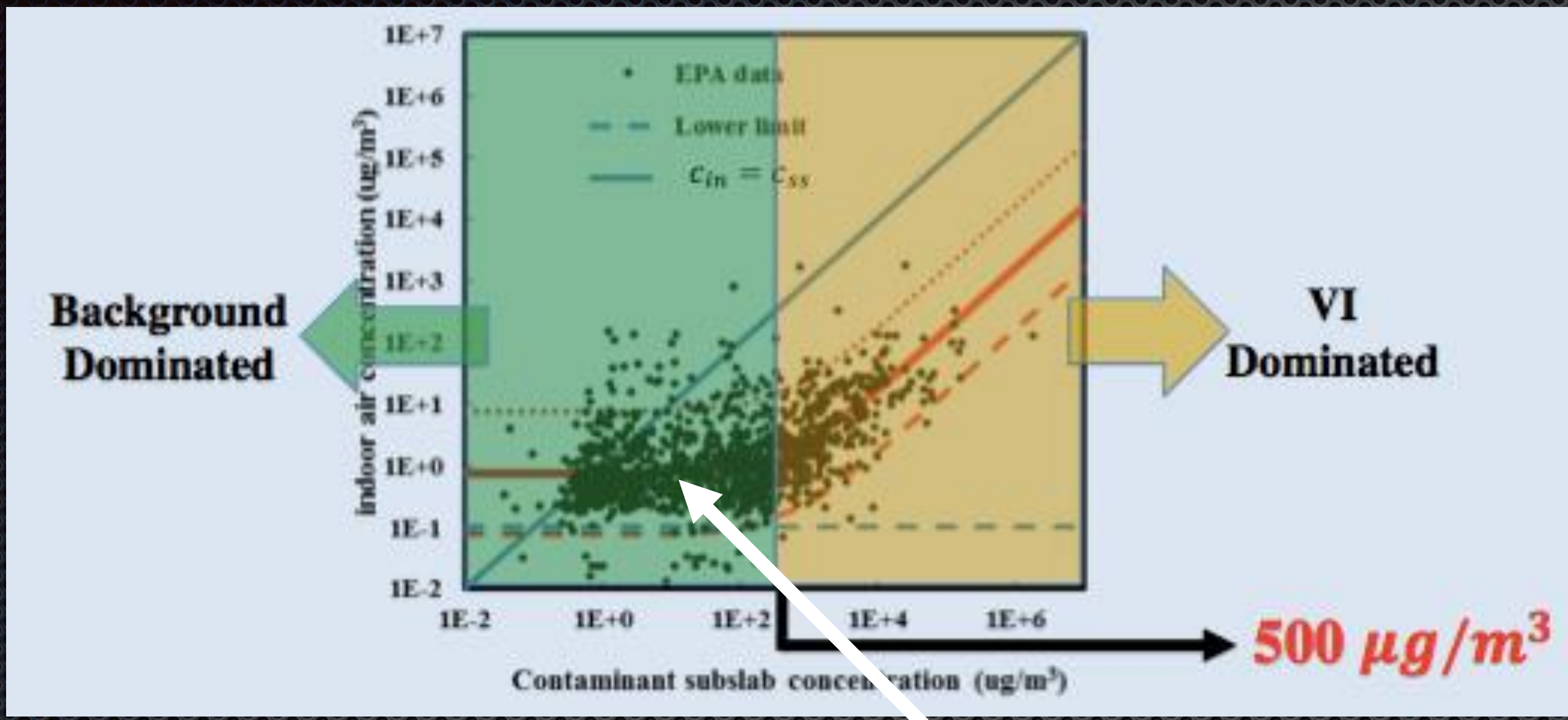
U.S. EPA uses empirical "attenuation factor" approach for predicting indoor air concentrations

- Based upon many field measurements.
- $C_{indoor}/C_{subslab}$ = 0.1 (resistance of slab)
- $C_{indoor}/C_{groundwater\ source}$ =0.001





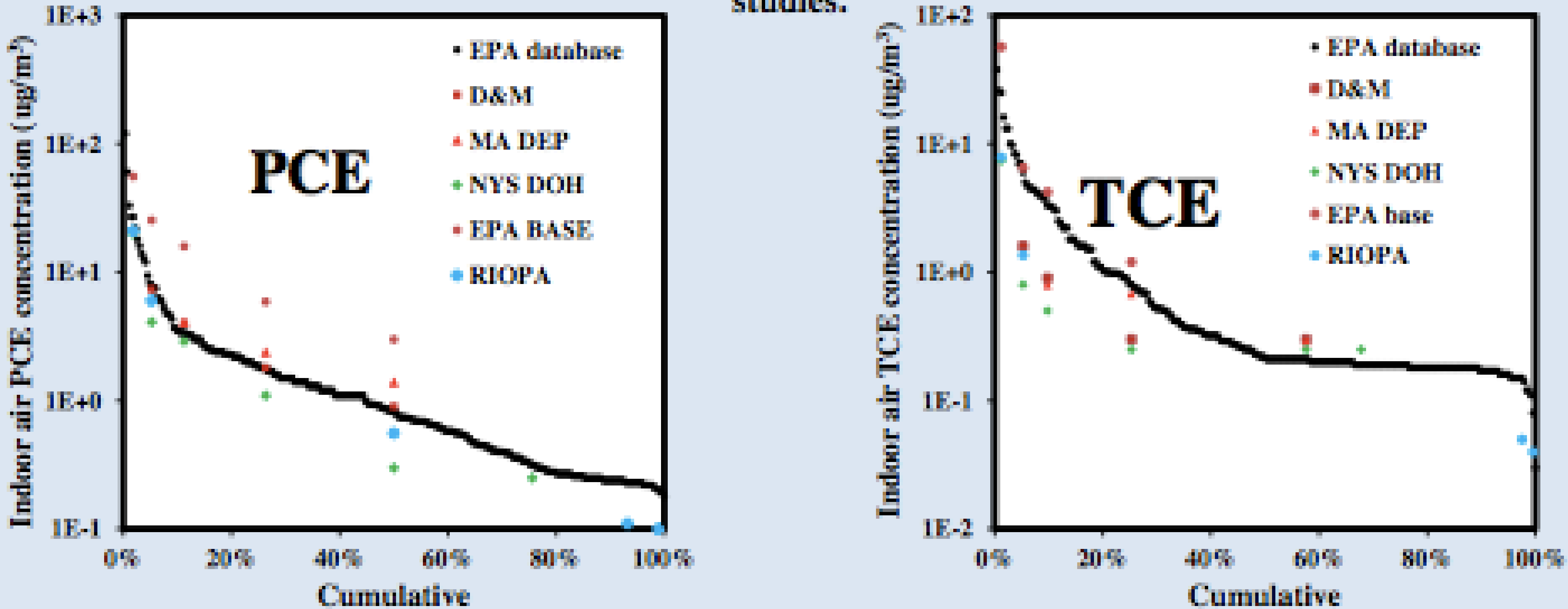
Groundwater Source- reflects resistance of soil plus slab



There is often great significance given to subslab values- but does this always make sense?

Little dependence of indoor air concentration on subslab values, because indoor air values dominated by “background” sources

Comparison between the EPA database indoor air results when c_{ss} <500 $\mu g/m^3$ and other non-VI background studies.



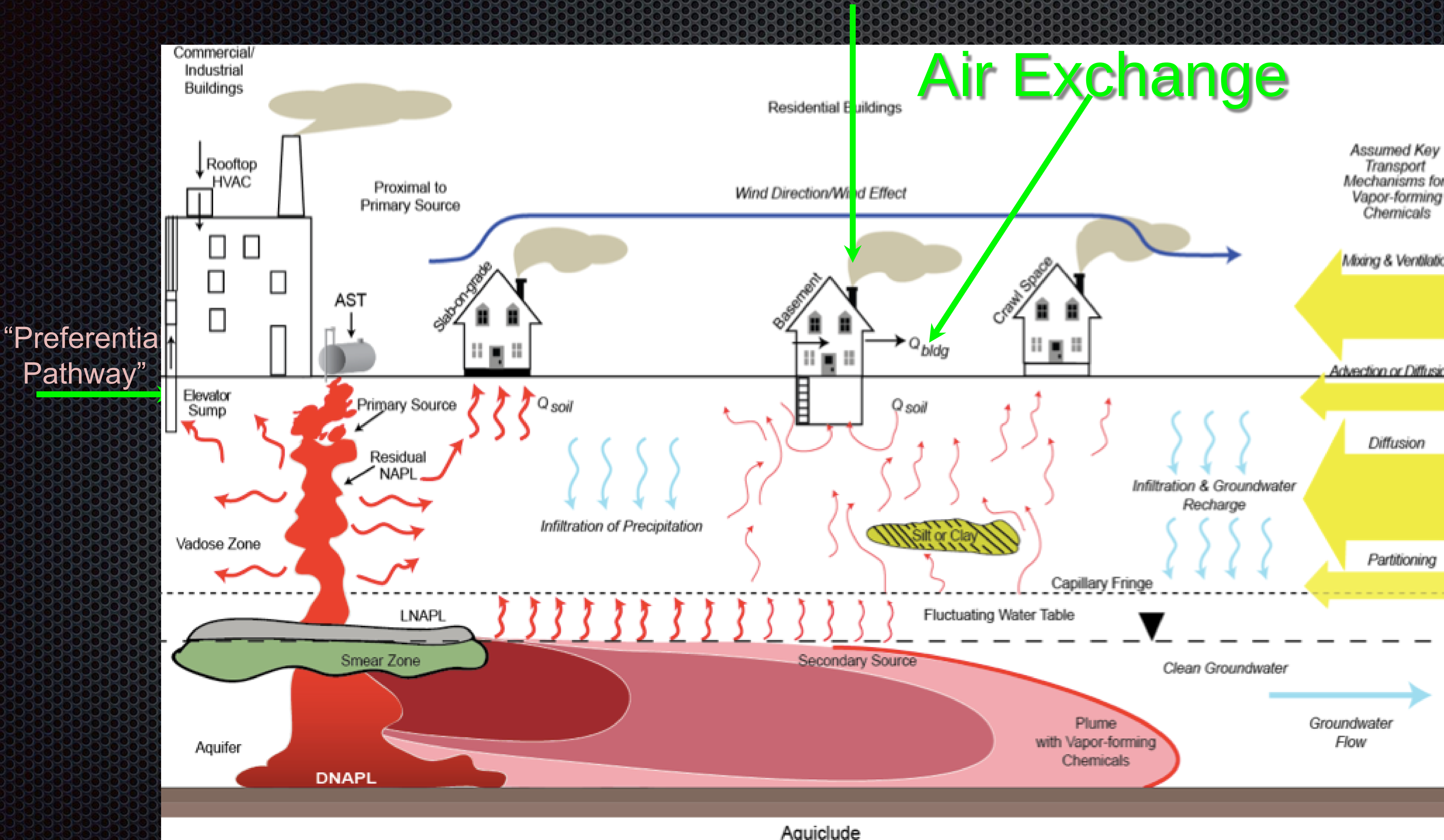
There is no significant difference seen in distributions between low subslab concentration cases and non-VI cases.

When do you really look to VI, as opposed to other sources (e.g., consumer products)?

A 1000 m^3 volume house, 2 $\mu g/m^3$ indoor air contaminant level has an air inventory of 2 mg contaminant- can sorption processes contribute to the observed phenomena?

Can we begin to do better by applying advanced engineering modeling tools?

“Stack Effect” Results in building depressurization of 1 to 50 Pa (5 Pa typical)



Adapted from Larry Schnapf, AWMA VI Conference Presentation, Cherry Hill, NJ 2014

EPA Screening Model Approach

- Based upon a 1-dimensional (1-D) model developed by Paul Johnson and Robbie Ettinger in 1991, based on earlier Radon work of Nazaroff and others.

$$\frac{D_{eff}*A_B}{L_T}\left(c_{source}-c_{ck}\right) = Q_{ck} * \frac{\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)c_{ck}-c_{indoor}}{\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)-1}$$

$$Q_{ck} * \frac{\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)c_{ck}-c_{indoor}}{\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)-1} = Q_{building} * c_{indoor}$$

$$\alpha = \frac{c_{indoor}}{c_{source}} = \frac{\frac{D_{eff}*A_B}{Q_{building}L_T}\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)}{\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)+\frac{D_{eff}*A_B}{Q_{ck}L_T}\left(\exp\left(\frac{Q_{ck}d_{ck}}{A_{ck}D^{ck}}\right)-1\right)+\frac{D_{eff}*A_B}{Q_{building}L_T}}$$

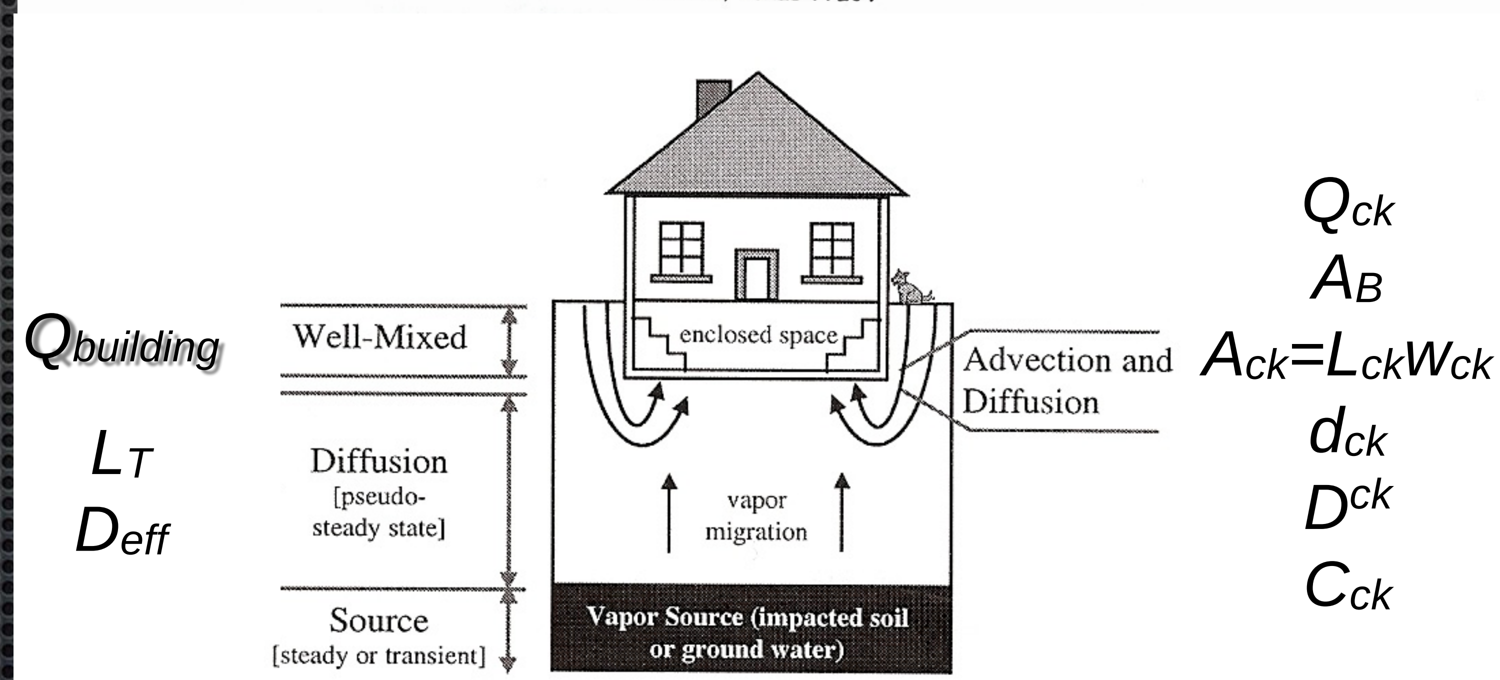
Everything leaving the source enters the house- unrealistic, but a consequence of 1-D.

Environ. Sci. Technol. 1991, 25, 1445–1452

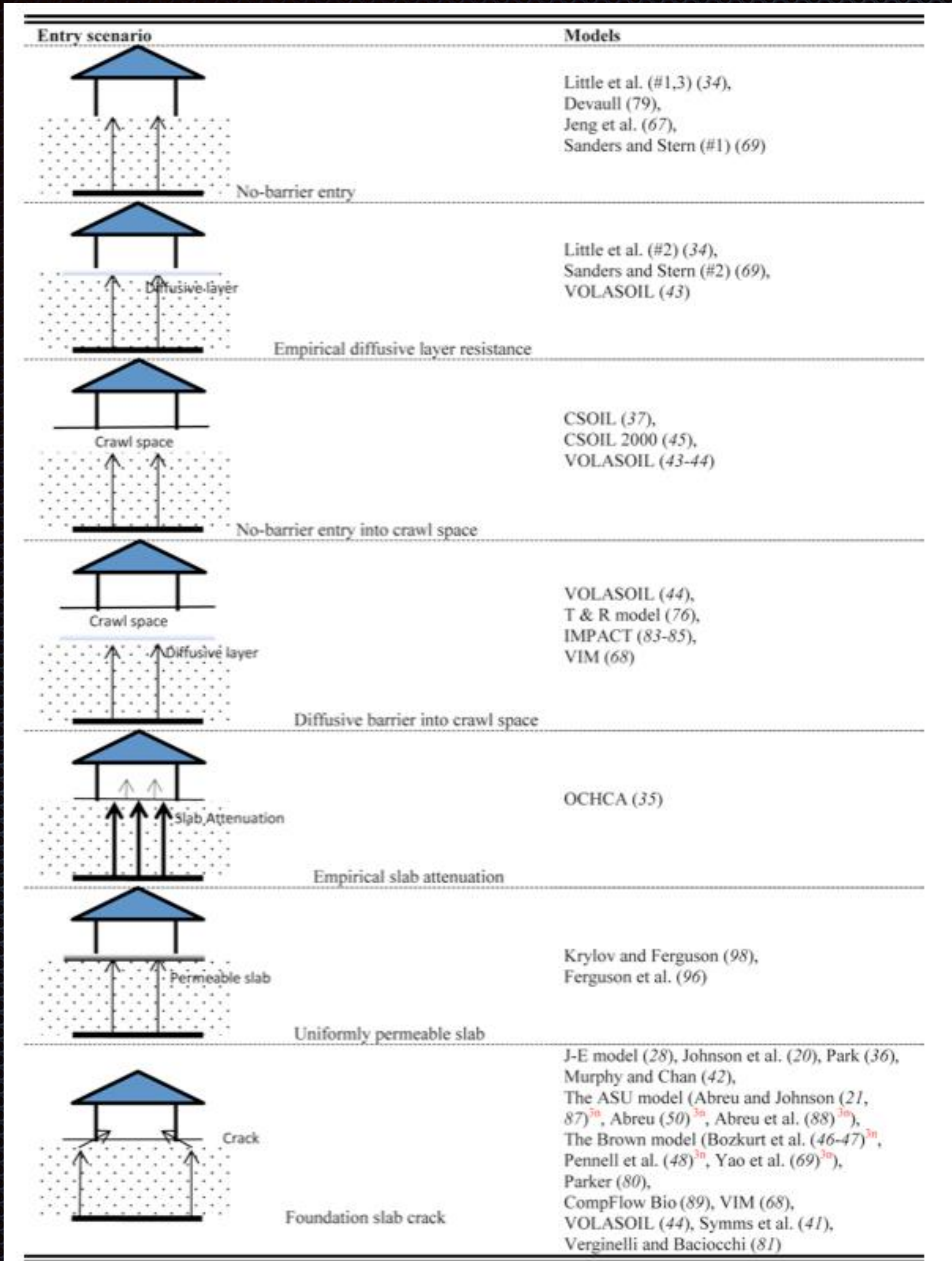
Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings

Paul C. Johnson* and Robert A. Ettinger

Shell Development, Westhollow Research Center, Houston, Texas 77251



Attenuation factor depends upon $Q_{building}$



Entry scenario	Models
No-barrier entry	Little et al. (#1,3) (*34*), Devaull (79), Jeng et al. (*67*), Sanders and Stern (#1) (*69*)
Diffusive layer Empirical diffusive layer resistance	Little et al. (#2) (*34*), Sanders and Stern (#2) (*69*), VOLASOIL (*43*)
Crawl space No-barrier entry into crawl space	CSOIL (*37*), CSOIL 2000 (*45*), VOLASOIL (*43-44*)
Crawl space Diffusive layer Diffusive barrier into crawl space	VOLASOIL (*44*), T & R model (*76*), IMPACT (*83-85*), VIM (*68*)
Slab Attenuation Empirical slab attenuation	OCHCA (*35*)
Permeable slab Uniformly permeable slab	Krylov and Ferguson (*98*), Ferguson et al. (*96*)
Crack Foundation slab crack	J-E model (*28*), Johnson et al. (*20*), Park (*36*), Murphy and Chan (*42*), The ASU model (Abreu and Johnson (*21*, *87*)[3n], Abreu (*50*)[3n], Abreu et al. (*88*)[3n]), The Brown model (Bozkurt et al. (*46-47*)[3n], Pennell et al. (*48*)[3n], Yao et al. (*69*)[3n]), Parker (*80*), CompFlow Bio (*89*), VIM (*68*), VOLASOIL (*44*), Symms et al. (*41*), Verginelli and Baciocchi (*81*)

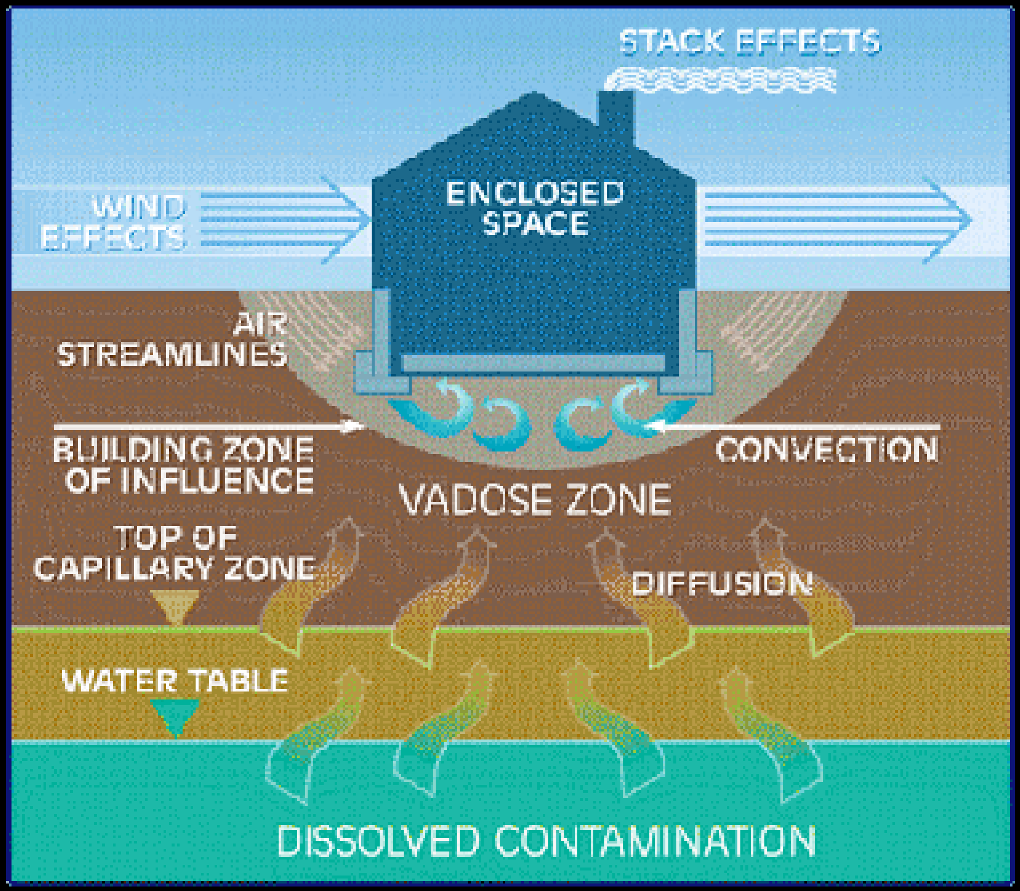
Many mathematical models of VI being developed worldwide.

Differ based on where the main attenuation is assumed

Source: Yao et al., *Env. Sci. Tech.*, *47*, 2457-2470 (2013).

Brown University Modeling Approach

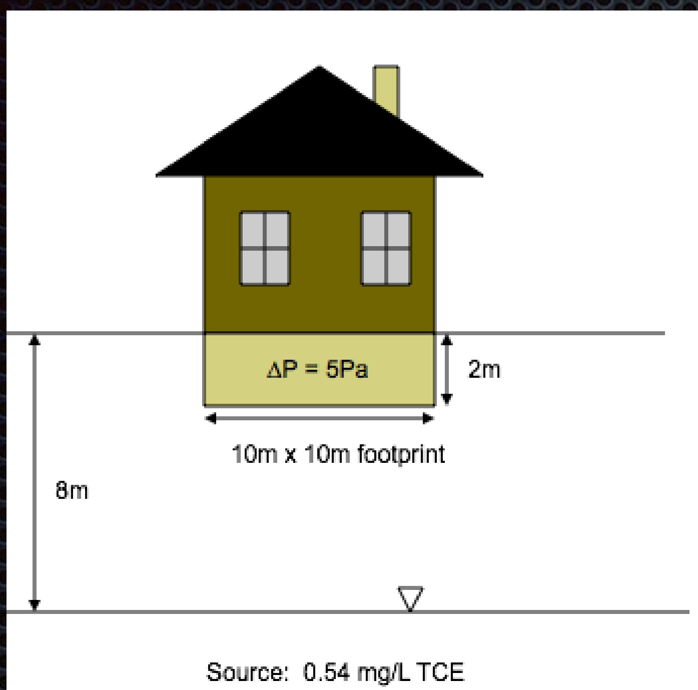
- A finite element computational package (Comsol) used to describe transport processes.

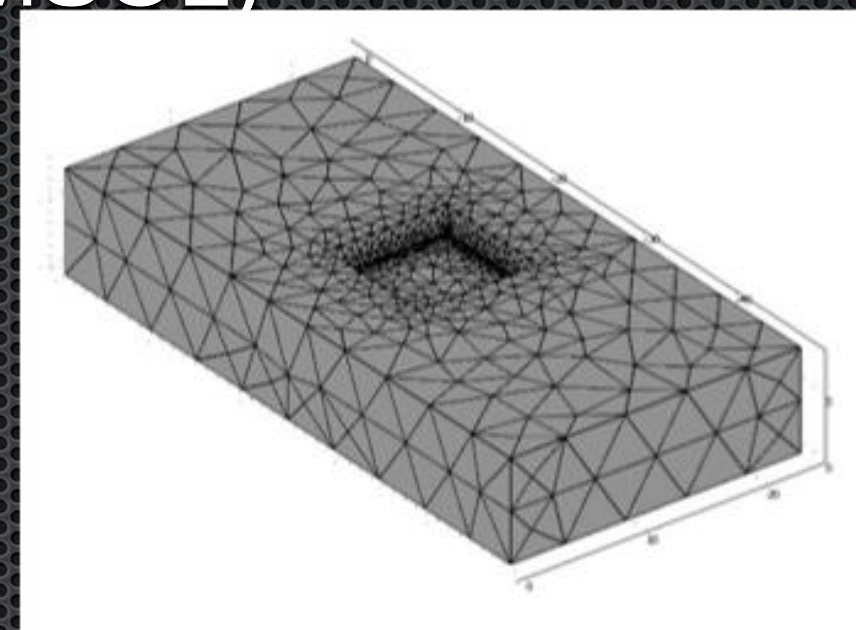


www.vaprotect.com/images/2006/10/17/graphic.gif

•Set finite element model domain.
•Typically assume a perimeter crack in the foundation.
•Assume “Stack Effect” creates an in-house negative pressure of 5 Pa.

3-D Modeling Approach- Finite Element Solver (COMSOL)





Typically model 5 mm perimeter cracks

3-step solution method

1. Solve for gas advective flow through soil (Darcy's Law).
2. Solve for species transport via advection and diffusion.
3. Indoor air concentration is calculated using the species flow rate into the structure.

$$q = \frac{-\kappa\rho}{\mu}\nabla\phi$$

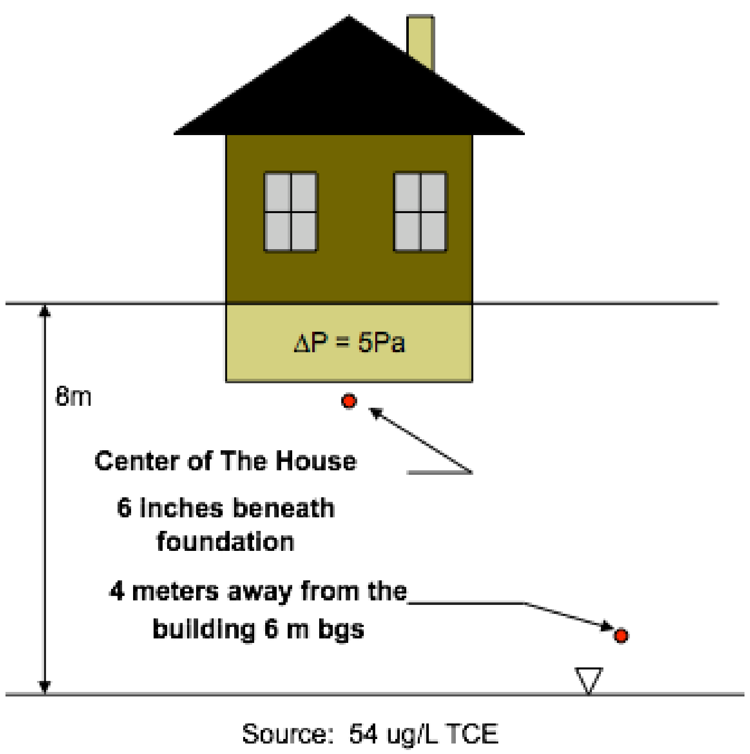
$$\phi = gz + \int_{Po}^{P}\frac{dP}{\rho}$$

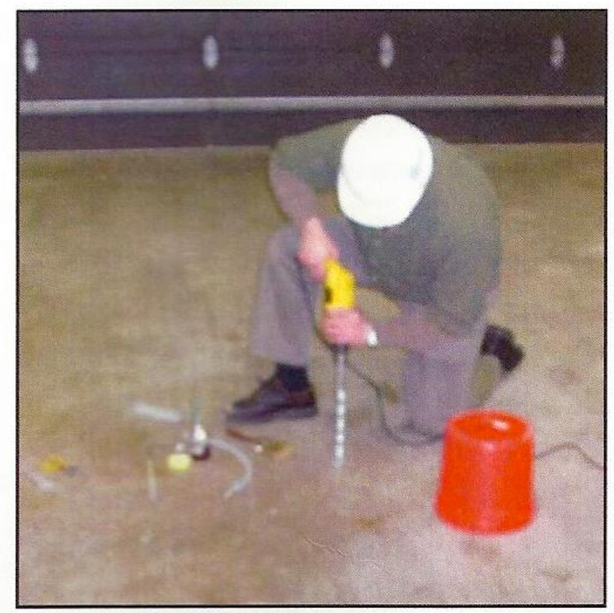
$$J_T = q\cdot C + D_{ig}\nabla C$$

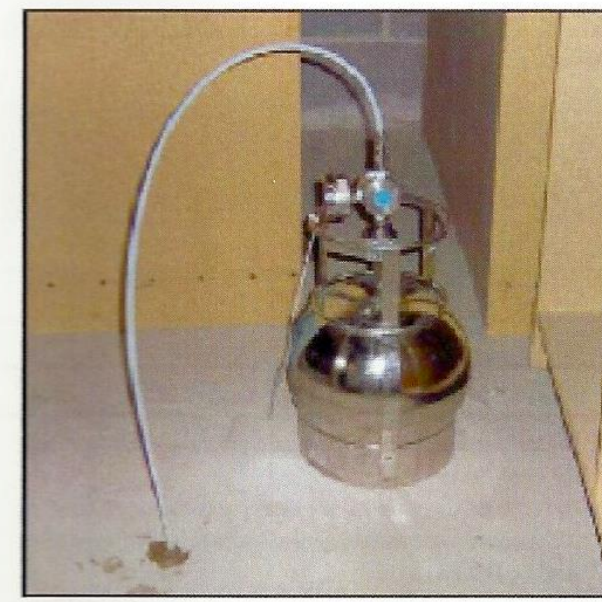
$$D_{ig} = d_i^{air}\cdot\frac{\eta_g^{10/3}}{\eta_T^{2}}$$

$$C_{indoor} = \frac{J_{Tck}}{A_e\cdot V_b + Q_{ck}}$$

Subslab Sample Reliability?







We simulated various sampling points at different depths and locations using a sampling rate of 6L/8hr.

Photos from O'Brien and Gere

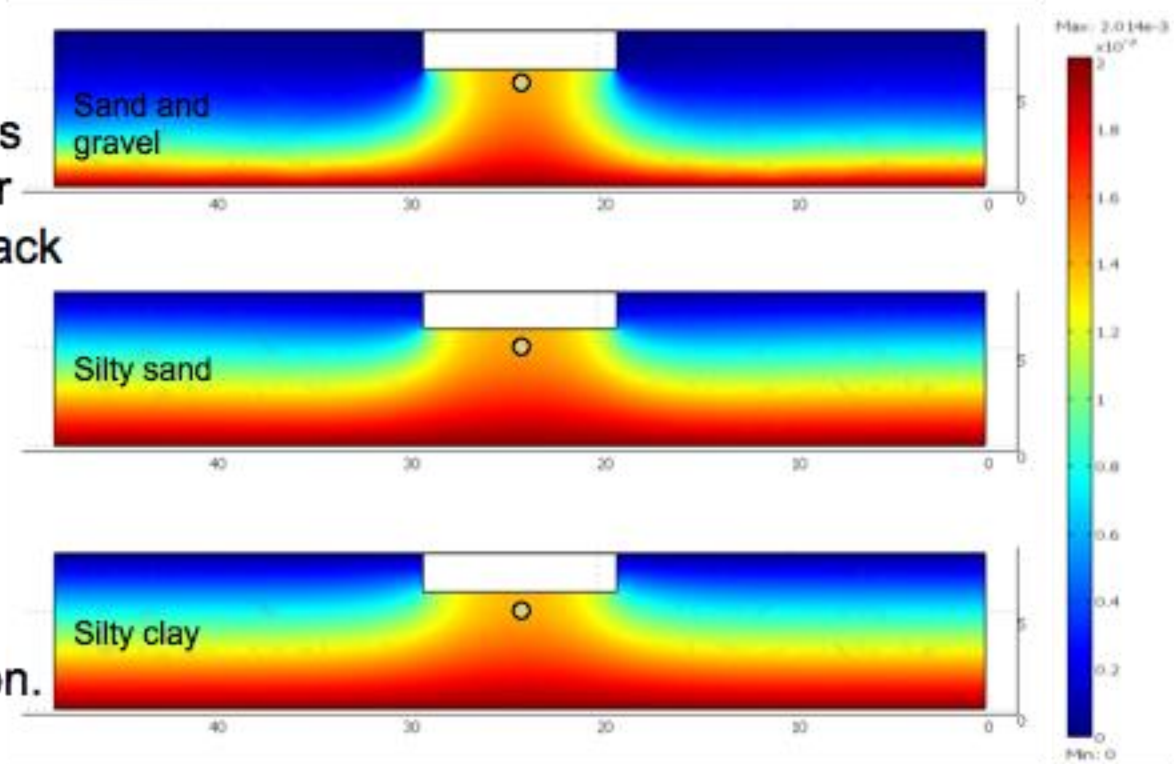
Subslab sample reliability?
Roughly same values, but 2 O.O.M. difference in indoor air

Where should samples be collected?

Center of The House Immediately beneath foundation	Permeability	C sampling location (mg/m³)	C indoor Air (mg/m³)	Soil Gas Entry Rate (L/min)	$C_{indoor}/C_{sampling}$
	High (10^{-10} m²)	217	1.78	47.5	8.20×10^{-3}
	Moderate (10^{-11} m²)	190	0.27	4.75	1.41×10^{-3}
	Low (10^{-14} m²)	174	1.86×10^{-2}	0.0048	1.07×10^{-4}

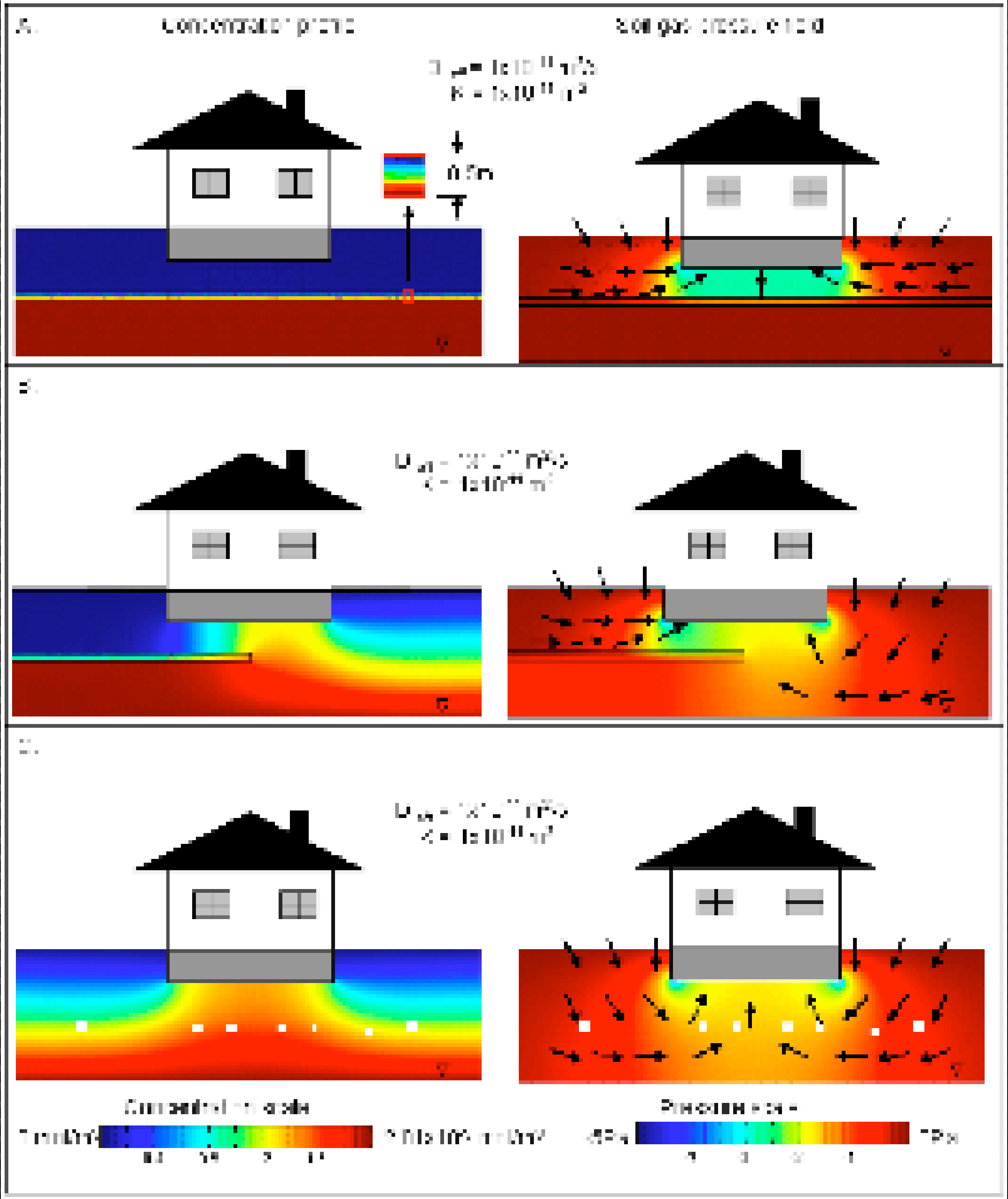
The concentration values at the sampling point for all three cases are very similar; however, higher soil gas flow rate through the crack carries more contaminant vapor into the building, causing higher indoor air concentration for high permeability cases.

Sub slab sampling may lead to incorrect conclusions about the indoor contaminant concentration.

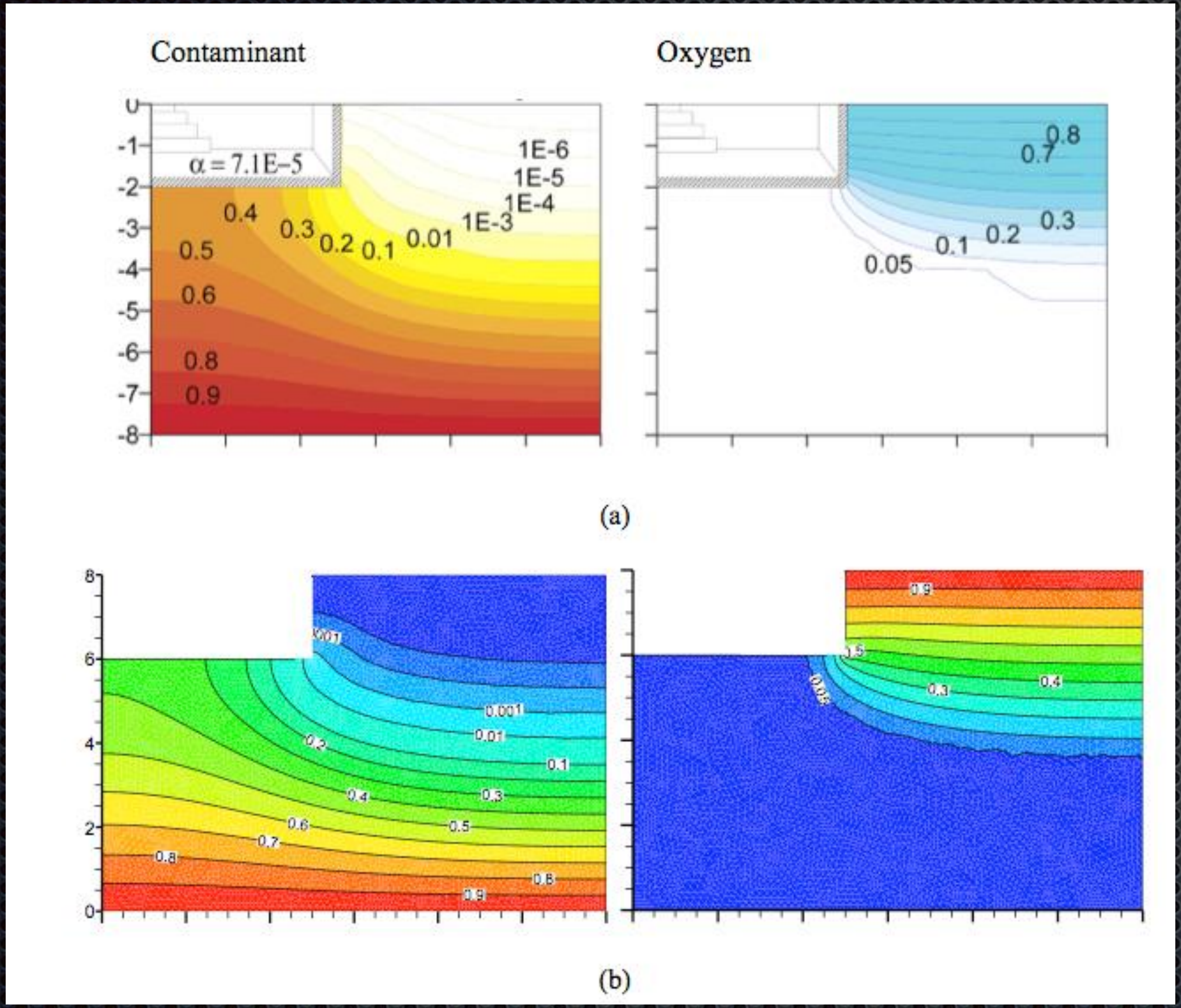


Clay layers, paving, and any relatively impermeable bodies in soil can really cause problems in understanding field results.

Lots of empirical data that "defy explanation"- need a good quantitative modeling analysis/good CSM.



Biodegradation Can Also be Modeled



Abreu and Johnson, *EST*, *40*, 2304-2315 (2006)

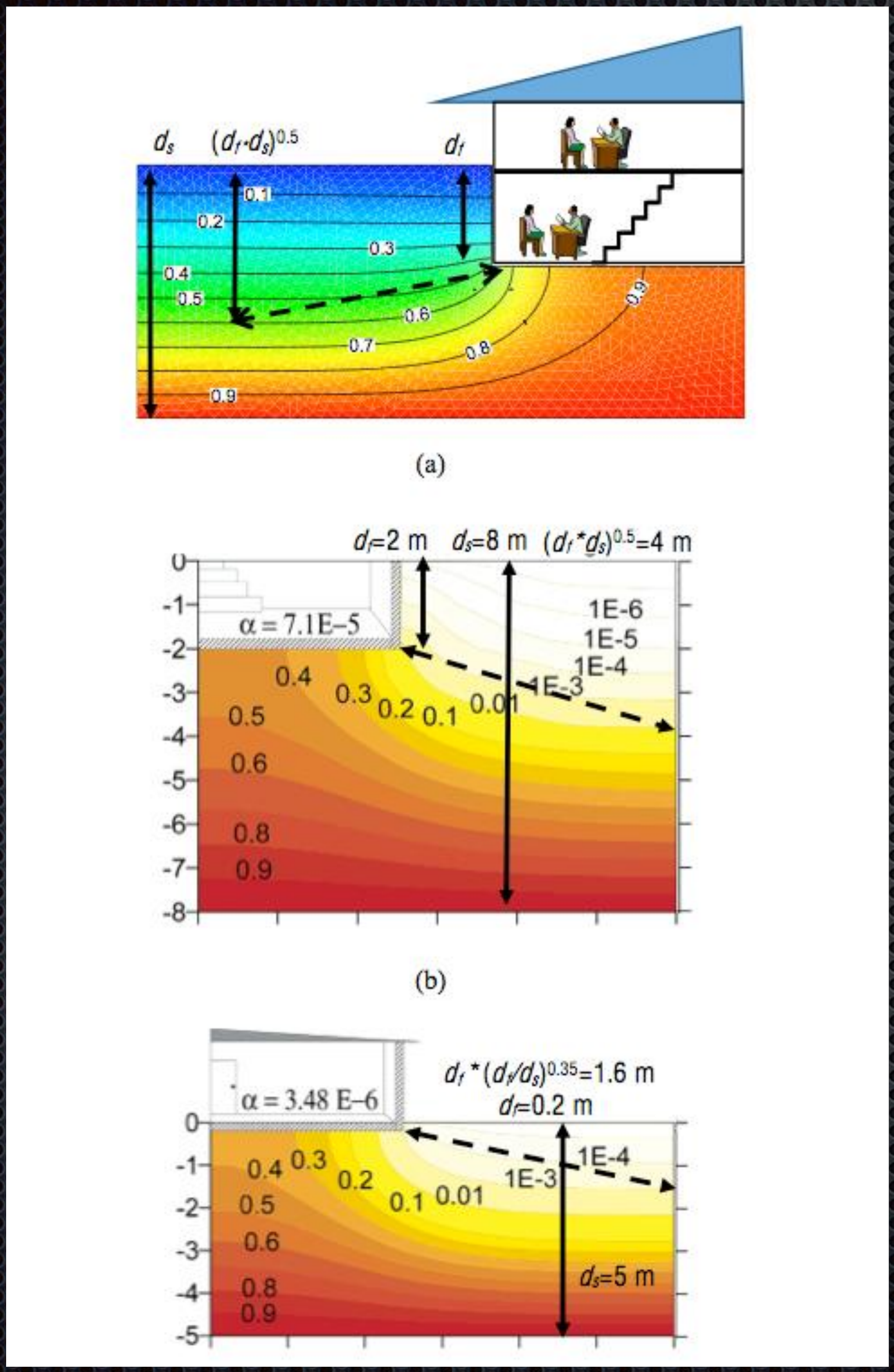
$$0 = -\nabla \cdot (q_g c_{ig}) + \nabla \cdot (D_i \nabla c_{ig}) - R_i$$

$$R_c = \frac{\lambda_2 \phi_w}{H_c} c_c c_o$$

Yao, 2012

$$\frac{dc_c}{dt} = -\frac{\lambda_2 \phi_w}{H_c \phi_g} c_c c_o$$

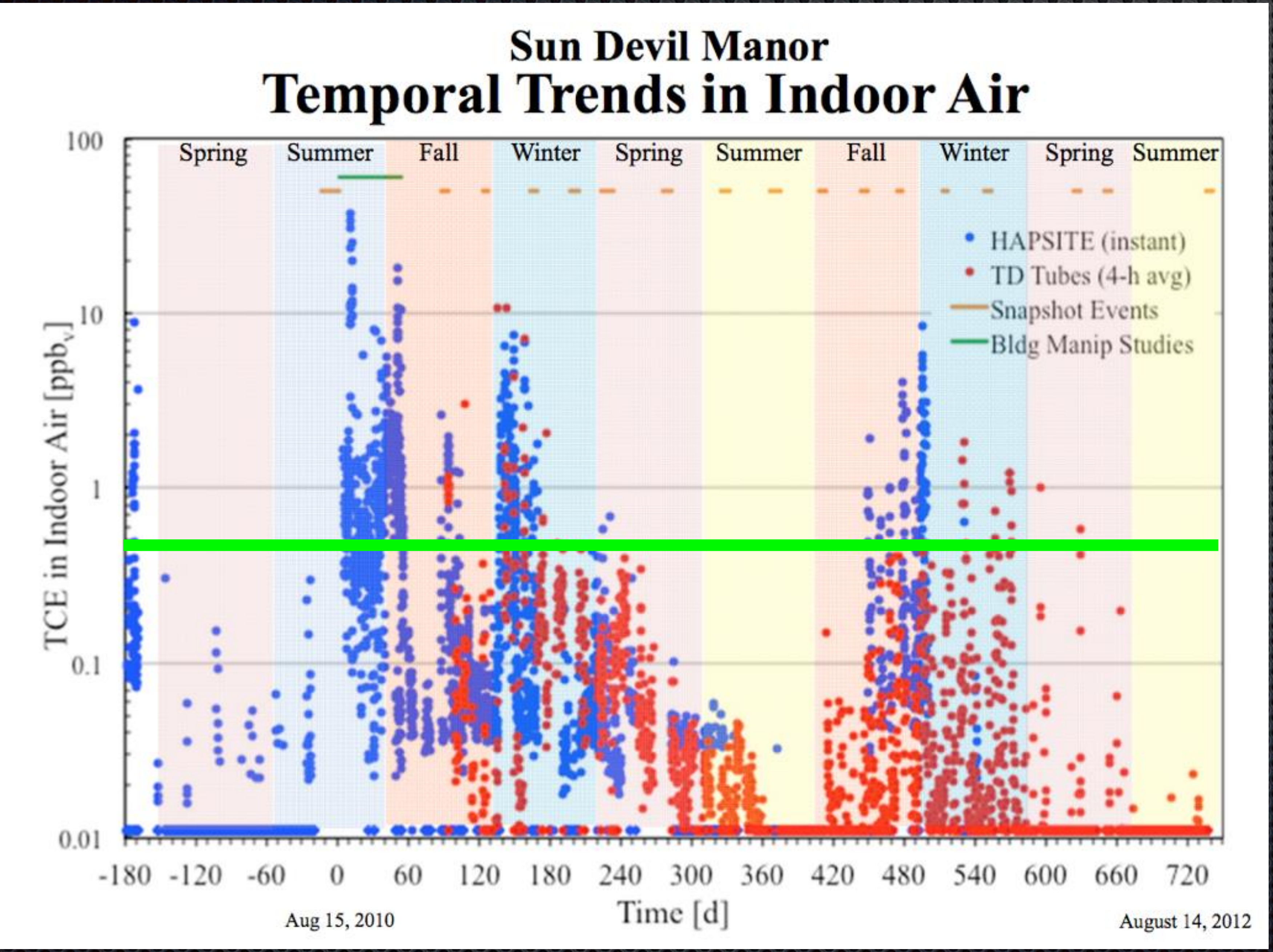
No agreement on if c_o should be explicit in models



Contaminant levels much decreased by biodegradation.

Key for petroleum- based compounds, not too important for chlorinated solvents (unless enhanced)

The new regulatory challenge- how to deal with the inherently transient nature of VI



Three O.O.M. variation in indoor air levels!
3.5% of days contribute > 50% of total exposure.
So what does one regulate for? Average? Few days of peak?

From a paper by Lutes, Johnson and Truesdale, AEHS, 2013, also see Holton et al., *EST* 2013.

Summary

- There exists a large variation in steady state Attenuation Factors, for reasons that are still only partly understood.
- Essential to consider background concentrations (and possibly sorption effects).
- There needs to be greater use of advanced mathematical modeling tools to begin to make more sense out of apparently conflicting field data, especially transient data.
- There needs to be awareness of transients, some very short term, some seasonal, and some very long time scale. What should be the regulatory response?

What is in the future?

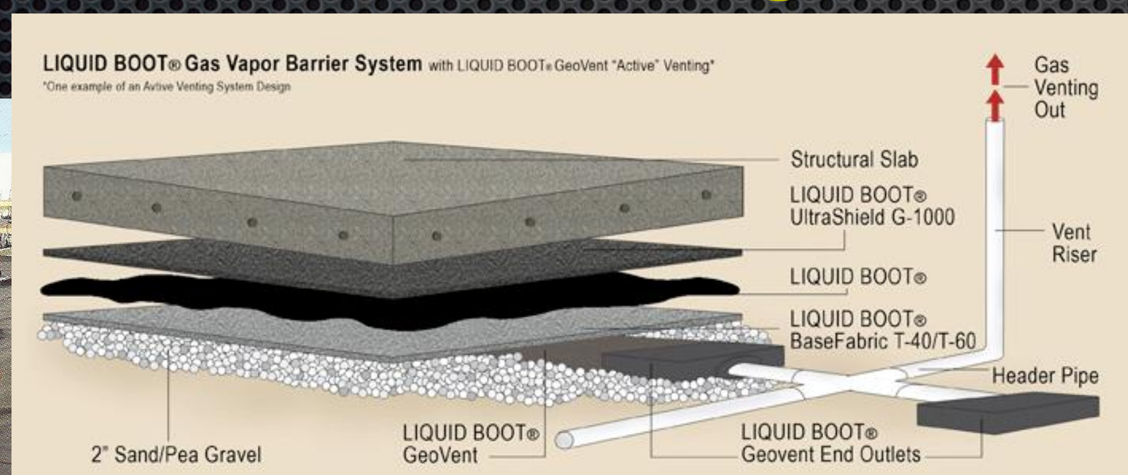
Advanced modeling will help guide better site investigations

Reliable site models will help in design of effective mitigation strategies

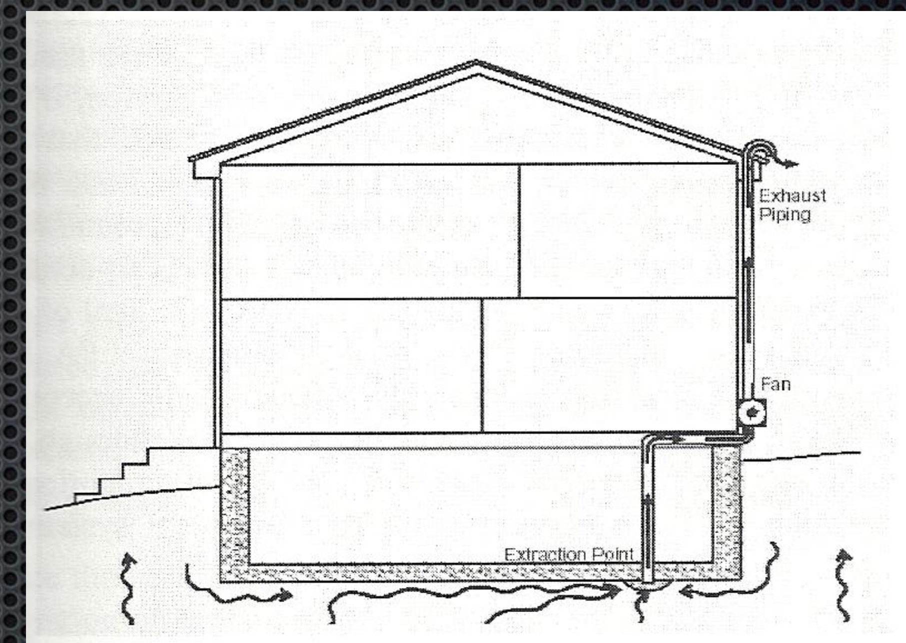
More robust models will help better define the transient nature of exposures and help in deciding upon appropriate regulatory responses.

So what can you do about it, if there is a problem?

Mitigation



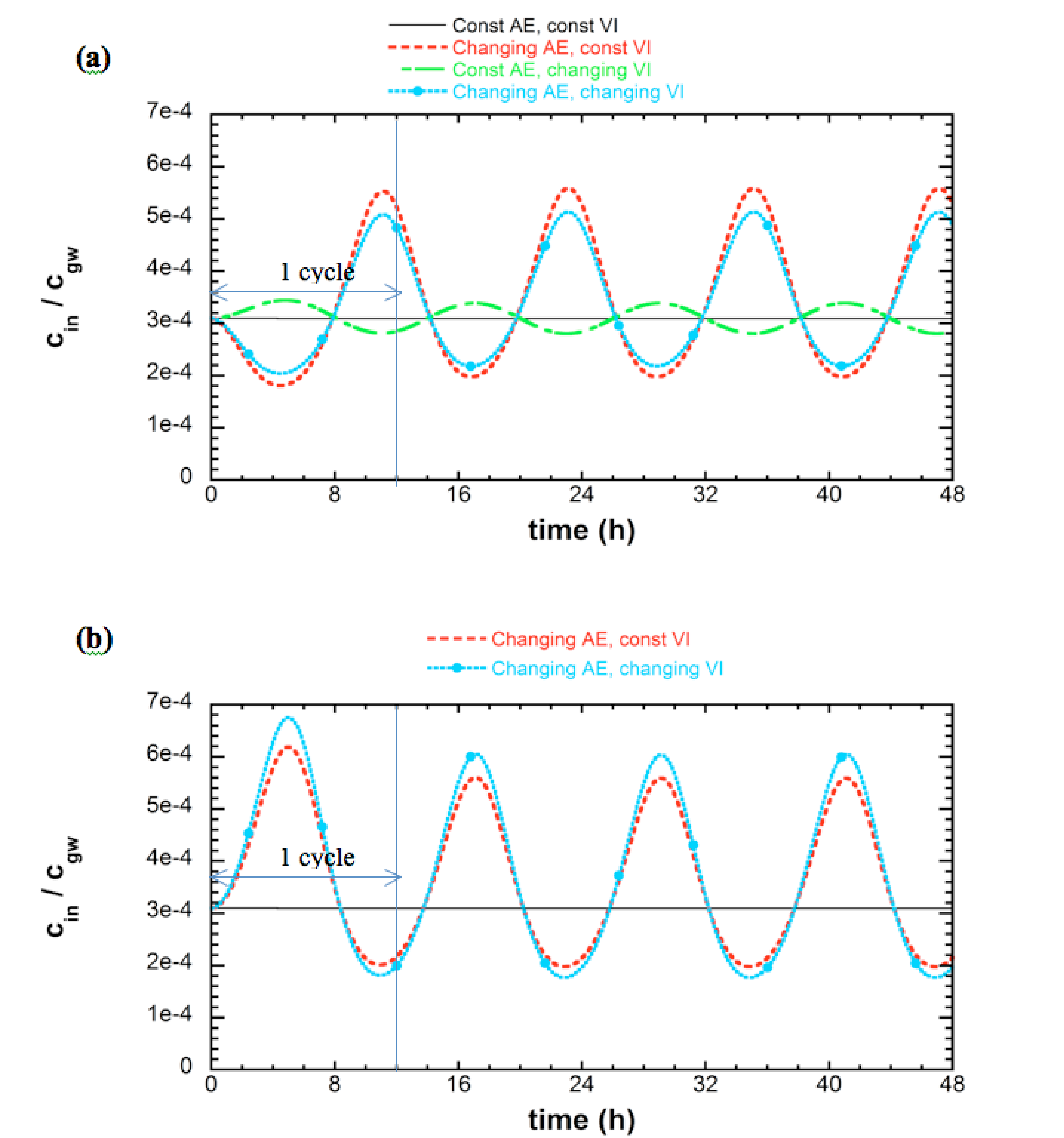
"Liquid Boot" water-spray applied chloroprene modified asphaltic emulsion from LBI Technologies/CETCO Environmental



Drawing from Gaurin and Wingert, 2007 AWMA Vapor Intrusion Conference

Subslab depressurization

Can also pressurize the building


(a)
Const AE, const VI
Changing AE, const VI
Const AE, changing VI
Changing AE, changing VI
1 cycle
c_{in} / c_{gw}
time (h)
(b)
Changing AE, const VI
Changing AE, changing VI
1 cycle
c_{in} / c_{gw}
time (h)