The Intricacies of Really Understanding Vapor Intrusion—and What This Means for Modeling

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**Vapor intrusion** involves the migration of chemical vapors in the soil and groundwater to enter buildings through foundation cracks and joints. Sometimes vapor intrusion can result in long-term exposure of contaminants at harmful levels.

- Affects maybe 1/4 of the estimated inventory of 500,000 US brownfields sites.
- At present, no general EPA guidance, though draft guidance has been prepared.
- States regulate, but often very different standards in use.
- Also jurisdictional issues - who is in charge - OSHA? EPA? State?
- No agreement on site investigation practices.
- Limited use of quantitative modeling - very fieldwork based, empirical.
In environmental health risk assessment, for there to be a human health risk there must be a completed exposure pathway, involving identification of a

- **Source** (But what if Source Strength is Variable?)
- **Migration Route** (What temporal variation is possible?)
- **Receptor** (Confounding receptor level situations?)

- Does depth to GW matter?
- Does rain/ice make a difference? Other Seasonal/weather effects?
- What about non-VI background?

*Interstate Technology & Regulatory Council, 2007*
So the first step is to decide if a chemical is of concern (a COC)

- Set a maximum allowable exposure, assuming 30 years in a home, 350 days a year at home, whether children are involved...

- Set a regulatory indoor air concentration for the COC ($C_{\text{indoor}}$)

- Widely varying, workplace to residence, state to state
Fundamental problem—extrapolation from animal data to low dose exposures

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

Also, can stop drinking polluted water, but replacing the 20 m³/day of air we breathe is tough.

May get indigestion (or worse), but what was meant was “ingestion.”
Results in building depressurization of 1 to 50 Pa (5 Pa typical)
U.S. EPA empirical “attenuation factor” approach for predicting indoor air concentrations

- $C_{\text{indoor}}/C_{\text{groundwater source}} = 10^{-4}$
- $C_{\text{indoor}}/C_{\text{subslab}} = 10^{-2}$ to $10^{-3}$
- Based upon empirical observation.

**Groundwater Source—fairly conservative**

\[ AF_{VI} = \frac{C_{IA-VI}}{C_{SS}} \times \frac{C_{SS}}{C_{SV}} \]

\[ AF_{VI} = AF_{bldg} \times AF_{soil} \]

overall vapor intrusion attenuation factor \((AF_{VI})\)
Table 2. Residential screening levels for selected VOCs.

<table>
<thead>
<tr>
<th>State</th>
<th>Benzene Groundwater</th>
<th>Benzene Soil Gas</th>
<th>TCE Groundwater</th>
<th>TCE Soil Gas</th>
<th>TCE Indoor Air</th>
<th>PCE Groundwater</th>
<th>PCE Soil Gas</th>
<th>PCE Indoor Air</th>
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<tbody>
<tr>
<td>Alaska</td>
<td>5</td>
<td>3.1</td>
<td>0.31</td>
<td>5</td>
<td>0.22</td>
<td>5</td>
<td>8.1</td>
<td>0.81</td>
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<td>California</td>
<td>NA</td>
<td>36.2</td>
<td>0.084</td>
<td>NA</td>
<td>528</td>
<td>1.22</td>
<td>NA</td>
<td>180</td>
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<td>Colorado</td>
<td>15</td>
<td>NA</td>
<td>0.23</td>
<td>5</td>
<td>NA</td>
<td>0.016</td>
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<td>Connecticut</td>
<td>130</td>
<td>2490</td>
<td>3.3</td>
<td>27</td>
<td>752</td>
<td>1</td>
<td>340</td>
<td>3798</td>
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<tr>
<td>Indiana</td>
<td>95-850</td>
<td>250-1400</td>
<td>2.5</td>
<td>4.6-700</td>
<td>120-2000</td>
<td>1.2-4.1</td>
<td>7.4-1100</td>
<td>320-5200</td>
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<td>Louisiana</td>
<td>2,900</td>
<td>NA</td>
<td>12</td>
<td>10,000</td>
<td>NA</td>
<td>59</td>
<td>15,000</td>
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<td>10</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Massachusetts</td>
<td>2000</td>
<td>NA</td>
<td>0.3</td>
<td>30</td>
<td>NA</td>
<td>1.37</td>
<td>NA</td>
<td>50</td>
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<tr>
<td>Michigan</td>
<td>5600</td>
<td>150</td>
<td>2.9</td>
<td>15,000</td>
<td>700</td>
<td>14</td>
<td>25,000</td>
<td>2100</td>
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<tr>
<td>Minnesota</td>
<td>NA</td>
<td>1.3-4.5</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>42</td>
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<td>2000</td>
<td>95</td>
<td>1.9</td>
<td>50</td>
<td>54</td>
<td>1.1</td>
<td>80</td>
<td>68</td>
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<td>15</td>
<td>16</td>
<td>2</td>
<td>1</td>
<td>27</td>
<td>3</td>
<td>34</td>
<td>3</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>5</td>
<td>NA</td>
<td>100</td>
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<td>Ohio</td>
<td>14</td>
<td>31</td>
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<td>-</td>
<td>122</td>
<td>12.2</td>
<td>11</td>
<td>81</td>
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<td>Oklahoma</td>
<td>5</td>
<td>3.1</td>
<td>0.27</td>
<td>5</td>
<td>0.17</td>
<td>0.017</td>
<td>5</td>
<td>0.33</td>
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<tr>
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<td>NA</td>
<td>0.27</td>
<td>6.6</td>
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<td>0.018</td>
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<td>Pennsylvania</td>
<td>3500</td>
<td>NA</td>
<td>2.7</td>
<td>14,000</td>
<td>NA</td>
<td>12</td>
<td>42,000</td>
<td>NA</td>
</tr>
</tbody>
</table>

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. *Second range of values shown is for subslab soil gas. *Chronic exposure value.
Implication is that states with higher GW screening levels tend to look for Attenuation Factors that are greater than the EPA average when compared to indoor air screening levels ($10^{-5}$ and $10^{-6}$) are the very tail of the distribution.

Data for CO, LA, CT, MA, NH, MI, PA. Henry’s Law constants for benzene, TCE and PCE from EPA website, 25°C
<table>
<thead>
<tr>
<th>State</th>
<th>Groundwater</th>
<th>Shallow Soil Gas</th>
<th>Deep Soil Gas</th>
<th>BTEX</th>
<th>Crawl Spaces</th>
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<tbody>
<tr>
<td>Alaska</td>
<td>0.001</td>
<td>0.1</td>
<td>0.01</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>California</td>
<td>NA</td>
<td>0.01 - 0.002</td>
<td>same as shallow</td>
<td>NA</td>
<td>0.002</td>
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<tr>
<td>Colorado</td>
<td>NA</td>
<td>0.1 (subslab)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Connecticut</td>
<td>0.001</td>
<td>0.001</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Indiana</td>
<td>NA</td>
<td>subslab = 0.1 soil gas = 0.01</td>
<td>0.01</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Louisiana</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Maine</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>Based on J&amp;E model</td>
<td>NA</td>
<td>NA</td>
<td>Adjusted by 10x</td>
<td>NA</td>
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<tr>
<td>Michigan</td>
<td>Based on J&amp;E model</td>
<td>0.02</td>
<td>0.002</td>
<td>NA</td>
<td>NA</td>
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<td>Minnesota</td>
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<td>New Hampshire</td>
<td>Based on J&amp;E model</td>
<td>0.02</td>
<td>0.02</td>
<td>Groundwater values adjusted by 10x</td>
<td>1</td>
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<tr>
<td>New Jersey</td>
<td>Based on J&amp;E model</td>
<td>0.02</td>
<td>NA</td>
<td>0.002</td>
<td>1</td>
</tr>
<tr>
<td>New York</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ohio</td>
<td>0.001</td>
<td>0.1</td>
<td>0.01</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>0.1 (subslab)</td>
<td>0.1 (8-10 ft)</td>
<td>NA</td>
<td>NA</td>
<td>1</td>
</tr>
<tr>
<td>Oregon</td>
<td>0.002</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>NA</td>
<td>0.01</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
For example, a 2000 µg/L screening level for benzene in groundwater, would imply roughly a 40 µg/m³ indoor air criterion, at an AF of $10^{-4}$.

The RIDEM GW GB cleanup standard for benzene is 140 µg/L, which translates to a 1.4 µg/m³ effective average indoor standard, based upon EPA average AF.
Even Henry’s Law can be a challenge...So what is \( C \) groundwater source?

Shallow groundwater temperatures (Collins, 1925)

Washington, 1996
The empirical Attenuation Factor includes contributions from the “true” Attenuation Factor \( AF_{VI} \) and (indoor) background. In EPA analysis, \( C_{sv} \) represents COC concentration at any reference point in the soil path (including at the source).

\[
AF_{EMP} = \frac{C_{IA}}{C_{SV}} = \frac{(C_{IA-VI} + C_{IA-BKGD})}{C_{SV}} = AF_{VI} + \frac{C_{IA-BKGD}}{C_{SV}}
\]

\[
AF_{EMP} = \left[ AF_{bldg} + \frac{C_{IA-BKGD}}{C_{SS}} \right] \times AF_{soil}
\]
It is a real effect, of concern in almost all data sets for the chlorinated solvents (i.e, TCE, PCE).
Need to watch what values you assume for background levels- they have gone down over time.

Source: Background Indoor Air Concentrations of VOCs in North American Residences: A Compilation of Statistics and Implications for Vapor Intrusion by Helen Dawson (EPA)

- A number of VOCs have typical (median) background concentrations above the $10^6$ risk level (benzene, carbon tetrachloride, chloroform, methylene chloride, PCE).
- Several others exceed $10^6$ risk levels about 10% of time (1,2-DCA, TCE, vinyl chloride).
How far is far enough??

Solved simple 2-D Laplace Equation

\[
D_x \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) = 0
\]

Lowell and Eklund, 2004

Echoed in various guidance documents, but challenged by Abreu and Johnson, 2005 for homogeneous soils.
How close should GW Source measurements be?

Consider 2 m deep basement, 4 m deep source, sampling GW at r = 5 i.e., 20 m away, can lead to significant extra attenuation

Yao et al. Vadose Zone Journal, 2013

Unusually high source to slab attenuation can have an origin in GW sources that are not really that “close”

Foundation to source depth

Subslab to Source Concentration
The Issue of Transients

Sample data from a 2013 AEHS Conference Workshop by Schumacher et al. Samples from a duplex in Indianapolis.

Note the wide variability over short sampling times.

Correlation with Radon not particularly good.

Seasonal variability in indoor air higher than in subslab.
Another example from Utah

From a paper by Lutes, Johnson and Truesdale, AEHS, 2013.
Different from Long Timescale Transient Situations

Darcy’s Law

$$\left( x_p (1 - \eta_g) + x_f \eta_g \right) \frac{\partial p}{\partial t} = \nabla \left( \frac{k}{\mu_g} \left( \rho_g g \nabla z + \nabla p \right) \right)$$

Advection and Diffusion

$$\frac{\partial C_{ig}}{\partial t} + \nabla (q_g C_{ig} - D_{ig} \nabla C_{ig}) + R_{ig} = 0$$

With sudden appearance of a source at $8 \text{ m-}$
shows typical response is diffusion rate determined
Time response of subslab concentration if the groundwater is “clean” at t=0 and the groundwater does not act as a sink.

the groundwater acts as a sink

Note the very long timescales of response to “remediation”
Variation in Heating Season-Driven Stack Effect

Not a large seasonal variation
Summary

- There exists a large variation in Attenuation Factors, for reasons that are only partly understood.
- Essential to consider background concentrations (and to measure or at least use current estimates).
- How close should a GW monitoring well be, to be reliable?
- There needs to be the awareness of transients, some very short term, some seasonal, and some very long time scale.