MIGRATION OF SOIL GAS VAPORS TO INDOOR AIR:

DETERMINING VAPOR ATTENUATION FACTORS USING A SCREENING-LEVEL MODEL AND FIELD DATA FROM THE CDOT-MTL DENVER, COLORADO SITE

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A SUMMARY OF RESEARCH RESULTS FROM API'S SOIL & GROUNDWATER TECHNICAL TASK FORCE

Introduction

With the advent of risk-based decision-making at petroleum and other chemical-release sites, screening-level models for the subsurface vapor -to- indoor air pathway are now being used to: a) identify scenarios for which there might be significant adverse impacts, b) determine when site-specific assessment is necessary, and c) develop target soil and groundwater screening levels. A range of approaches for addressing this pathway have been proposed and debated for the past decade. At the extremes are approaches relying solely on screening-level predictive models and approaches requiring indoor air sampling. Intermediate are approaches that combine screening level models and site-specific sampling, as presented in API Publication 4674 (Johnson et al., 1998).

To date, objective comparison of the strengths and weaknesses of the various approaches and screening models has been difficult because of the scarcity of data and experience. However, with the growing interest in this pathway, more extensive data sets are becoming available. One such data set comes from the Colorado Department of Transportation Materials Testing Laboratory (CDOT-MTL) Site located in Denver Colorado. This data set is of particular interest because of the large number (>1000) of groundwater, soil gas, and indoor air concentration data, and the fact that the multi-event sampling was conducted at a number of locations. Johnson et al. (2001) provides a detailed analysis of this data set, featuring a comparison between: a) empirically derived attenuation factors for the soil vapor –to- indoor air pathway using measured groundwater and indoor air concentrations, with b) attenuation factors estimated using the Johnson and Ettinger screening-level model and reasonable input values for this site. Below, a

brief overview of that analysis is given and followed by a summary of the key findings of that study.

Overview of the CDOT-MTL Site and the Empirical Data Analysis

The CDOT-MTL site is located in Denver, Colorado. It has functioned as a central testing laboratory for pavement materials, paints, and other transportation-related research since 1957. Historical records show that the primary chlorinated compounds used at CDOT-MTL were 1,1,1 TCA (1,1,1 trichloroethane), TCE (trichloroethylene), and DCM (dichloromethane). Documents report that chlorinated solvents were accidentally released from two on-site underground storage tanks installed in the early 1970's. This resulted in contamination of soils, groundwater, and soil gas. For comparison, target analytes at this site include 1,1,1 TCA, 1,1,2 TCA, 1,1 DCA, 1, 2 DCA, 1,1 DCE, 1, 2 DCE, PCE and TCE. It is not clear if some of these are present because they were produced by chemical degradation of TCA and TCE, or if they were used at the site, or if they were impurities in the original solvents. Figure 1 shows the dissolved 1,1 DCE groundwater plume emanating from the site.

Soil, groundwater, soil gas, and indoor and outdoor air samples were collected. The data base contains the results from over 1000 samples. Prior to use in the analysis, the data were examined by methods described in Johnson et al. (2001), to ensure the quality of the data.   For this work, the data quality analysis consisted of: a) removing all non-detect values from the groundwater, indoor air, and soil gas data sets, and then b) looking for data consistency within each data set, and across data sets. Data quality analysis was especially valuable when dealing with the soil gas –to- indoor air pathway, because:

- It is common for non-detect vapor and groundwater concentrations to be entered in environmental databases as one-half the detection level; these values must be removed as the actual concentration in that sample is unknown (otherwise one may inadvertently end up determining relationships between non-detect levels in the subsurface and indoor air).

- It is important to establish a conclusive connection between concentrations of chemicals found in the subsurface and those found in indoor air as there is the potential for other indoor and outdoor sources of the chemicals of interest.

2

The data was next used to calculate "attenuation factors" (α), where α is the ratio of the indoor air concentration of some chemical divided by the equilibrium soil gas concentration of that chemical immediately above the source.   Johnson and Ettinger (1991) define the "attenuation factor" α to be the ratio of the indoor air concentration of some chemical i $C_{indoor}(i)$ divided by the equilibrium soil gas concentration $C^*_{source}(i)$ of that chemical at the source. For the case of steady groundwater sources, the definition of α is given by:

$$\alpha = \left[\frac{C_{indoor}(i)}{C^*_{source}(i)} \right] = \left[\frac{C_{indoor}(i)}{H(i)\, C_{groundwater}(i)} \right]$$

where $C_{groundwater}(i)$ and $H(i)$ denote the groundwater concentration and Henry's Law Constant for the chemical i of interest.

Thus, calculation of attenuation factors (α) is straight-forward when one has groundwater and indoor air concentrations at the same location, and both are relatively stable with time. Unfortunately, the CDOT-MTL data set does not contain synoptic samplings; that is, groundwater samples and indoor air samples were collected at different times, locations, and with different frequencies (i.e., groundwater wells are not located beneath the buildings). However, review of the data showed relatively stable groundwater concentrations with time and variations in indoor air samples were less than an order of magnitude (and typically less than a factor of three). Therefore, the following approach was adopted:

- Groundwater concentrations in all wells were averaged with time over a three-year period. That data was then contoured and concentrations beneath individual apartments were assigned based on those contour plots.

- Indoor air data was used as is, and attenuation factors were calculated for each sampling event.

Table 1 summarizes the results of that analysis. Empirically-derived attenuation factors fall in the range 10^{-6} to 10^{-4}, with an overall average of 3 x 10^{-5} [(mg/L-indoor air)/(mg/L-soil gas)].
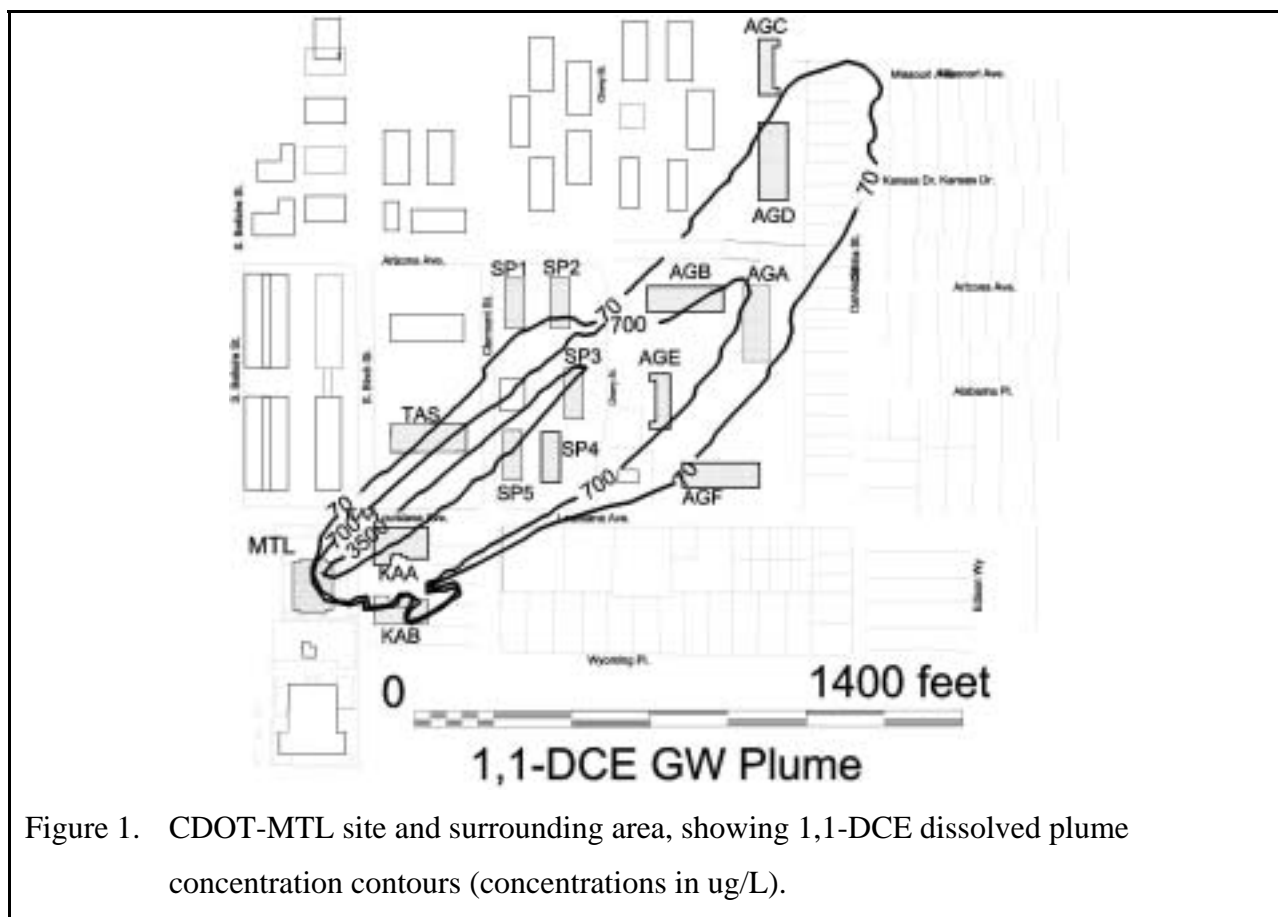
Figure 1.   CDOT-MTL site and surrounding area, showing 1,1-DCE dissolved plume

concentration contours (concentrations in ug/L).

Table 1.   Summary of empirical results from the analysis of the CDOT-MTL site data.

Chemical [# of data points]	1,1,1 TCA [145]	1,1 DCE [145]	TCE [111]	1,1 DCA* [90]
Average α	4.2×10^{-5}	1.3×10^{-5}	3.6×10^{-5}	3.4×10^{-4}
90th Percentile α	6.6×10^{-5}	2.0×10^{-5}	7.0×10^{-5}	3.4×10^{-4}
Geometric Mean α	1.7×10^{-5}	4.8×10^{-6}	1.4×10^{-5}	6.2×10^{-5}
• 1,1,1-trichloroethane (1,1,1 TCA); 1,1-dichloroethene (1,1 DCE); trichloroethylene (TCE) and 1,1-dichloroethane (1,1 DCA) • Overall Average α (1,1,1 TCA, 1,1 DCE, TCE data only): 3×10^{-5}				

* - note, this data set is suspected of containing a systematic error

The average α values by chemical for 1,1,1 TCA, 1,1 DCE, and TCE are quite similar, while the

average α value for 1,1 DCA is one order-of-magnitude greater. Theory suggests that the ranges

and average α values should be similar because the relevant steady-state transport parameters

(i.e., diffusion coefficient) are very similar for most chemicals and partitioning parameter

differences are already corrected for in the way that α is calculated. Given the relative

4

consistency between attenuation factors for 1,1 DCE, 1,1,1 TCA, and TCE, we hypothesize that the 1,1 DCA concentrations in either soil gas or groundwater were subject to a systematic error causing the reported 1,1 DCA α values to be about an order-of-magnitude greater than actual values.

Comparison with Estimates Given by the Johnson and Ettinger Model

Next, the utility of the Johnson and Ettinger (1991) model was assessed by using reasonable ranges of CDOT site-specific inputs to generate a range of attenuation factor estimates. The results of that analysis are summarized below in Table 2. The estimates range from 5×10^{-6} to 2×10^{-4} with a best estimate of 9×10^{-5} [(mg/L-indoor air)/(mg/L-soil gas)].

Lessons Learned

While this analysis provides us measured attenuation factor values that can be used for reference in the future, there are other equally valuable lessons that can be learned from this work.

First, the quantitative comparison of screening level model attenuation factor estimates with values calculated using the field data demonstrates that the Johnson and Ettinger (1991) screening level model was capable of predicting reasonable values for this site. Estimates agreed well with field data-derived values to within an order-of-magnitude, which is a reasonable expectation for a screening-level model. Use of a reasonable range of input values also helped to assess the sensitivity of the screening level model to its inputs and to identify key field data that could be use to reduce the uncertainty. Johnson (2002) discusses the primary critical parameters for the Johnson and Ettinger (1991) screening model and parameter sensitivity. A summary of the critical parameters can be found in Appendix A.

Second, this data quality analysis exercise provides insight to the challenges associated with assessment of this pathway via indoor air sampling. To draw any technically-defensible conclusions about the impacts of subsurface contaminants on indoor air at a given site, one must first have data that conclusively establishes a link between subsurface and indoor air concentrations. The mere presence of a chemical in both the subsurface and indoor air is in general insufficient to establish that linkage, given the high potential for other above-ground and

Table 2.   Inputs for Johnson and Ettinger model for the CDOT Site and the resulting attenuation factor α estimates (using TCE chemical properties).

Parameter	Lower Bound α Estimate	Upper Bound α Estimate	Best α Estimate
Depth to Groundwater [cm]	610	305	457
Capillary Fringe Height [cm]	50	10	20
Soil Porosity [vol/vol]	0.35	0.45	0.40
Vadose Zone Moisture Saturation [% of porosity]	0.45	0.25	0.35
Capillary Zone Moisture Saturation [% of porosity]	0.90	0.80	0.80
Q_{soil} [L/min]	1	10	10
η [area cracks/total area]	0.0005	0.005	0.001
Building Height [cm]	366	305	305
Air Exchange Rate [h^{-1}]	0.5	0.45	0.45
Basement Footprint [cm^2]	8.9×10^5	8.9×10^5	8.9×10^5
Attenuation Factor Estimate	4.8×10^{-6}	2.4×10^{-4}	8.6×10^{-5}

indoor sources of many volatile organic chemicals of interest. Short of adding tracers, or having chemicals for which no other sources exist, one must rely on observation of changes in indoor air concentration with changes in subsurface concentrations to establish this linkage. This can be accomplished by observing changes with time at one or more points, or by observing concentrations at different spatial locations. The former is likely to be impracticable at many sites due to characteristic transport times in the subsurface; thus, measurement in many residences overlying a wide range of concentrations is necessary.

Although soil-gas data is reasonably easy to collect, care should be taken in borehole logging, installing vapor probes, and sample collection. Proper sample QA/QC should also be performed (i.e., duplicate samples, field/trip blanks, internal standards). Analysis of the soil gas data from the CDOT-MTL site indicates that the soil gas data set does not behave as expected with depth. Fundamental considerations dictate that soil gas concentrations should consistently increase with

depth when the vapor source is groundwater. It is possible that the soil gas samples were compromised by leakage of atmospheric air along the sampling points and cross-contamination between samples and locations. Full analysis of the soil-gas data is presented in Johnson et al. (2001).

In light of this discussion it is important to note that the CDOT-MTL site is unique in terms of the extent of available data; groundwater, soil gas, and indoor air sampling data is available for a multi-year period and over a large spatial area. It also unique in terms of the amount of money allocated for direct measurement, assessment costs are well in excess of $1,000,000 (US). In contrast, the more typical conventional assessment by direct measurement involves one or two sampling events in a single residence.

Thus, assessing the significance of the subsurface-to-indoor air pathway via direct measurement is likely to be impracticable at many sites. A more cost-effective and practicable approach would involve the use of site assessment data and screening-level models to identify those sites that warrant further investigation by direct measurement. Some level of site assessment data is necessary as the screening level estimates would be too uncertain without it; however, it is anticipated that the required data would not represent a significant increase in data collection relative to current practices. For example in the CDOT-MTL site, reasonable screening level model estimates were achieved using limited site assessment data (depth to groundwater, qualitative soil boring log data, and approximate building/residence characteristics).

Finally, it is important to remember that: a) the conclusions and observations from this site are most applicable to other sites having relatively recalcitrant dissolved groundwater contaminants; b) it is expected that the magnitude of attenuation may be more substantial at sites where the contaminants of concern are naturally more readily degradable; c) it is also expected that the magnitude of attenuation may be less where the contaminant vapor source is located in the vadose zone; and d) the data supports the validity of the Johnson and Ettinger (1991) for cases where degradation is expected to be insignificant, but not for situations involving more readily degradable compounds. Modifications to that model to include degradation terms have been given in Johnson, et al. (1998) and development of other refinements are in progress (Johnson et al. 2000).

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Appendix A
Critical Parameters for the Johnson and Ettinger (1991) Vapor Intrusion Model

As discussed in Johnson (2002), α depends only on three basic parameters:

$$A = \left[\frac{D_T^{eff}}{E_B \left(\frac{V_B}{A_B}\right) L_T} \right], \qquad B = \left[\frac{\left(\frac{Q_{soil}}{Q_B}\right) E_B \left(\frac{V_B}{A_B}\right) L_{crack}}{D_{crack}^{eff} \, \eta} \right], \qquad C = \left[\frac{Q_{soil}}{Q_B} \right] \qquad (1)$$

where:

A_B = the surface area of the enclosed space in contact with soil [m^2]

D_{crack}^{eff} = the effective overall vapor-phase diffusion coefficient through the walls and foundation cracks [m^2/d]

D_T^{eff} = the effective overall vapor-phase diffusion coefficient in soil between the foundation and the depth L_T [m^2/d]

L_{crack} = the enclosed space foundation thickness [m]

L_T = the depth to the vapor source or other point of interest below foundation [m], measured from the foundation to the vapor source or other point of interest

Q_B = the enclosed space volumetric air flow rate [m^3/d] of fresh air; usually estimated to be the product of the enclosed-space volume (V_B [m^3]) and the indoor air exchange rate with outdoor air (E_B [1/d])

Q_{soil} = the pressure-driven soil gas flow rate from the subsurface into the enclosed space [m^3/d]

η = the fraction of enclosed space surface area open for vapor intrusion [m^2/m^2]; this is sometimes referred to as the "crack factor" and is estimated to be the total area of cracks, seams, and any perforations of surfaces in contact with soil divided by the total area in contact with soil.

Parameters A, B, and C appearing in Equation (1) are written in terms of (Q_{soil}/Q_B), (V_B/A_B), η, L_{crack}, L_T, D_T^{eff}, D_{crack}^{eff}, and E_B. This modified set of primary inputs is used because: a) reasonable values for (V_B/A_B) and E_B are constrained to narrow ranges, b) use of the ratio (V_B/A_B) eliminates the possibility of users assigning inconsistent V_B and A_B values, c) use of the ratio (Q_{soil}/Q_B) eliminates the possibility of users assigning inconsistent Q_{soil} and Q_B values, and d) the literature provides more clues for selection of reasonable (Q_{soil}/Q_B) ratios than individual

Q_{soil} values. The quantities E_B and V_B represent the enclosed-space air exchange rate [d^{-1}] and enclosed-space volume [m^3], and these are related to Q_B through the expression:

$$Q_B = V_B E_B \qquad (2)$$

In brief, α is at most linearly sensitive to changes in each of the primary inputs. Vapor attenuation will also be sensitive to biodegradation of degradable compounds such as benzene.