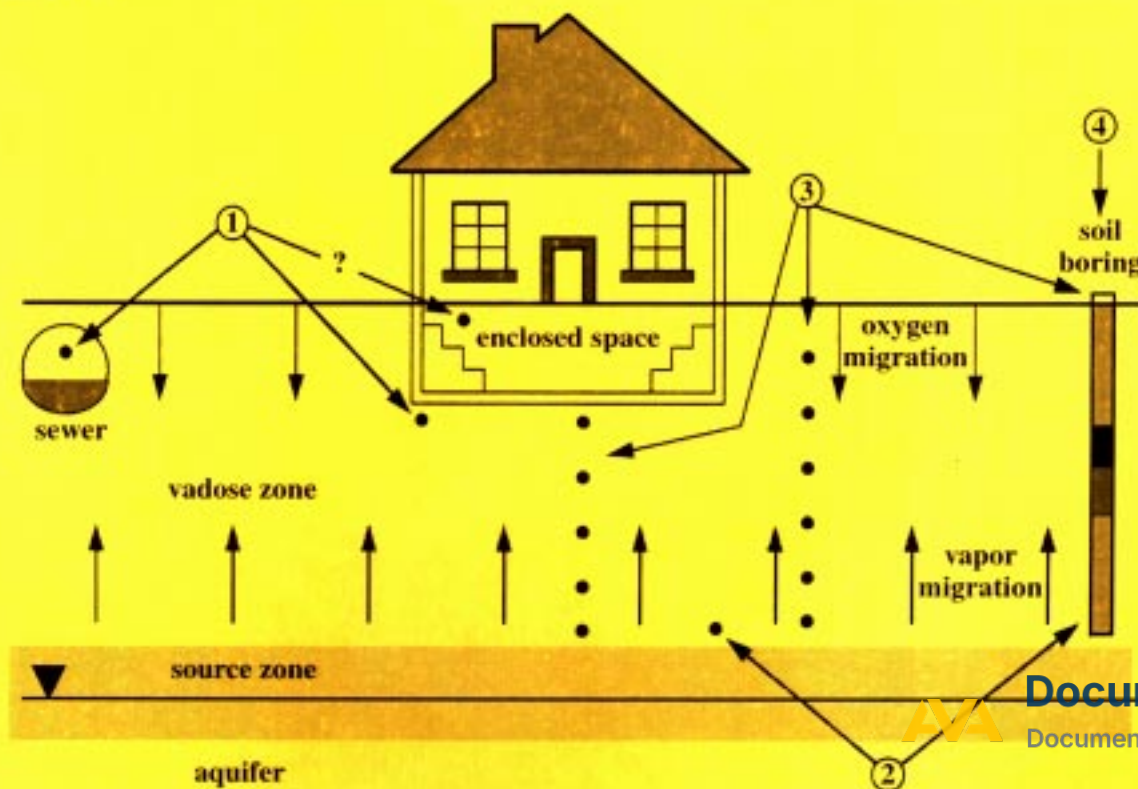


ASSESSING THE SIGNIFICANCE OF SUBSURFACE CONTAMINANT VAPOR MIGRATION TO ENCLOSED SPACES

SITE-SPECIFIC ALTERNATIVES TO GENERIC ESTIMATES

HEALTH AND ENVIRONMENTAL SCIENCES DEPARTMENT
PUBLICATION NUMBER 4674
DECEMBER 1998



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Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces

Site-Specific Alternative to Generic Estimates

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4674

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Executive Summary

The move toward more structured risk-based corrective action (RBCA) approaches has led to an interest in better understanding vapor migration to enclosed spaces. The significance of this pathway is currently the subject of intense debate, with many believing that existing non-site-specific risk-based (“generic” or “Tier 1”) screening levels are too conservative. As little data are available to justify generic approaches, this pathway must be addressed on a more site-specific basis. This document provides options for addressing the vapor migration pathway on a more site-specific basis.

Vapors in enclosed spaces pose two levels of concern. First, enclosed-space vapors may be found at concentrations near those that pose immediate flammability and/or health risks. These sites warrant immediate attention and response as required by most state and federal regulatory guidance. In the second class of sites, concentrations are lower and the concern is for longer term health risks. This report focuses exclusively on this second class of sites, where advection and diffusion occur through a soil layer and into an enclosed space and time is available to adequately address the problem on a site-specific basis.

The options considered in this document for refining generic vapor migration calculations and assessing the significance of this pathway on a more site-specific basis include:

- a) direct measurement through sampling of enclosed-space vapors,
- b) use of near-foundation or near-surface soil gas sampling results,
- c) use of site-specific homogeneous and layered soil diffusion coefficient estimates in generic algorithms, and
- d) assessment of bio-attenuation potential.

Data requirements, data presentation, and data interpretation are discussed and illustrated for each option. As discussed in the document, it is envisioned that options (c) and (d) will be used much more often than options (a) and (b) for the assessment of longer term impacts, due to a variety of technical and practical considerations.

Also, a vision for a simpler site-specific assessment approach is presented and accompanied by a discussion of the steps necessary to progress toward that goal. This improved approach considers bio-attenuation, but requires only soil moisture content measurements, or alternatively, in-situ diffusion coefficient measurements, to screen sites.

1.0 INTRODUCTION

When soils are impacted by leaks or spills, or wastes are placed in impoundments, the potential exists for contaminant vapor migration to enclosed spaces (buildings, conduits, etc.) and leachate migration to groundwater. Regulations have historically considered the leachate impacts on groundwater; however, the issue of vapor migration has only recently been formally and quantitatively considered. This focus has been brought about in large part by the move toward more structured risk-based corrective action (RBCA) approaches (e.g., ASTM 1995), coupled with an increased awareness of this pathway.

The significance of the vapor intrusion pathway and natural attenuation of vapors in the vadose zone is currently the subject of intense debate. When common screening-level algorithms (e.g., Johnson and Ettinger 1991, Little *et al.* 1992) are combined with conservative soil properties, geometries, and exposure assumptions, the resulting risk-based screening levels (RBSLs) are very low. In fact they are often one-tenth to one-thousandth the existing cleanup guidelines in many states. For example, the sample calculation in the ASTM RBCA Standard (ASTM, 1995) suggests that benzene concentrations in excess of 5 µg/kg-soil could be of concern if one wishes to be protective to a 10^{-6} excess cancer risk level.

Many intuitively feel that the current generation of screening-level predictive models is too conservative and leads to unnecessarily low cleanup levels. Some point to the fact that the algorithms generally do not account for biodegradation and other possible vadose zone attenuation mechanisms. It is reasonable to expect that some chemicals of interest degrade as they migrate, especially those originating from petroleum spills (e.g., benzene). If this is true, then these chemicals should be found at concentrations much less than those predicted by the current generation of screening level algorithms. This hypothesis is supported to some degree by the Fitzpatrick and Fitzgerald (1997) Massachusetts indoor air survey, the data of Fischer *et al.* (1996), and others who have observed and reported on petroleum hydrocarbon biodegradation in the vadose zone under natural conditions (e.g., Ostendorf and Kampbell 1991).

Unfortunately, little data exist to refute or support existing algorithms, or to quantify the degree of over-conservatism. This lack of data is a result of many factors, including the fact that interest in this pathway is relatively new. From a comparison of model predictions with published radon intrusion data, Johnson *et al.* (1991) and Little *et al.*

(1992) conclude that the screening algorithms should predict reasonable results when contaminants are present in soil gas immediately adjacent to a basement (e.g., Nazaroff *et al.* 1987). Yet to be reported are rigorous comparisons of model predictions and measurements for well-characterized sites where the contaminant sources are located at a distance from the buildings. Recently, Fitzpatrick and Fitzgerald (1997) presented their conclusions from a study of Massachusetts sites where indoor air samples were collected. Their goal was to review site characteristics and then identify specific trends and field conditions that most influence vapor migration and vapor intrusion into buildings. They also were interested in assessing the validity of generic state guidance derived from use of the Johnson and Ettinger (1991) algorithm. In summary, they noted that the generic Massachusetts guidelines overestimated vapor intrusion impacts for petroleum fuel hydrocarbon sites; however, they also found that the generic screening guidelines sometimes under-predicted indoor concentrations at sites where chlorinated organic vapors were present. Contrary to the popular belief that the models are overly conservative, the authors concluded that the generic Massachusetts guidelines were not conservative enough for site screening purposes, at least for chlorinated compound sites.

Given limited data and limited understanding, the potential for high sensitivity to site-specific conditions, and the tendency to lean toward conservativeness when developing regulations, it seems unlikely that technically defensible alternatives for developing generic screening levels will surface in the near-term. The inevitable consequence is that many sites containing volatile carcinogens are unlikely to satisfy generic RBSLs for this pathway. Thus, this pathway will need to be addressed on a more site-specific basis, and options are needed to ensure that this is done in a technically defensible manner. Some state-level regulatory agencies are already struggling with developing site-specific guidance for assessing this pathway.

In answer to this need, options for addressing the vapor migration pathway on a more site-specific basis are proposed here. These include more refined use of existing screening algorithms for layered geologic settings, as well as use of updated algorithms that consider biodegradation. These options stem from consideration of available data, existing algorithms, theoretical considerations, and empirical experience (Jury *et al.* 1983, Kampbell *et al.* 1987, Nazaroff *et al.* 1987, Garbesi and Sextro 1989, Jury *et al.* 1990, Johnson *et al.* 1990, Loueiro *et al.* 1990, Ostendorf and Kampbell 1990, Johnson and Ettinger 1991, Johnson and Perrot 1991, Hodgson *et al.* 1992, Little *et al.* 1992, Unlu *et al.* 1992, Ostendorf 1993, Jin 1994, Acomb *et al.* 1996, Auer *et al.* 1996, Fischer *et al.*

1996, Jeng et al .1996, Lahvis and Baehr 1996, Smith *et al.* 1996, Uchrin 1996, BP 1997, DeVaul *et al.* 1997, Li 1997, Sextro 1997, Stout 1997). The data collection and data reduction activities can easily be arranged in a sequence of increasing complexity, increasing data requirements, and likely increasing cost. Whether or not this approach is reasonable and defensible can only be determined by application to actual field sites followed by review of the results and experiences. It is recognized that with application, knowledge will continue to grow, and opinions and recommended practices are likely to evolve and become refined over the next few years.

In order to provide insight to the technical challenges, the reader is first provided an introduction to current approaches for developing generic risk-based screening levels, and a discussion of other technical considerations important to the development of the options described here. This is followed by the proposed array of options for assessing the significance of the vapor intrusion pathway on a more site-specific basis. At the end of this report, a vision for a much simpler site-specific assessment is presented and accompanied by a discussion of the developments necessary to progress toward that goal.

2.0 CURRENT APPROACHES FOR DEVELOPMENT OF GENERIC RBSLs

For reference, Figure 1 presents a conceptual model of the situation of interest. The concern here is the potential for adverse impacts due to contaminant vapors emanating from vadose zone soils, impacted capillary fringe soils, or dissolved chemicals in groundwater.

Incidence of vapors in enclosed spaces fall into two major classes. In one class, enclosed-space vapors are found at concentrations near those that could cause immediate impacts (e.g., fire, explosion, acute health risks, etc.). This is most often due to a direct or highly permeable connection (e.g., electrical conduit, gasoline entering a sewer, etc.) between a flammable liquid/vapor and the enclosed space. This class of sites deserves immediate attention and response as required by most state and federal regulatory guidance. In the second class of sites, the concern is with diffusion and advection from the vapor source through a soil layer and into an enclosed space. This report focuses exclusively on this second class of sites, where the concern is for longer term health effects and time is available to adequately address the problem on a more site-specific basis.

Screening level algorithms for the vapor intrusion pathway (Johnson and Ettinger 1991, Little *et al.* 1992, Johnson and Kemblowski 1998) couple source zone partitioning, vadose zone transport, building foundation transport, and enclosed-space mixing algorithms. The resulting algorithms then depend on parameters related to soil, chemical, and building characteristics. ASTM (1995), USEPA (1996), and some state regulatory agencies have used the Johnson and Ettinger (1991) algorithm to relate the estimated indoor vapor concentration C_{indoor} [mg/m^3] to the source zone vapor concentration C_{source} [mg/m^3]:

$$\alpha = \frac{C_{\text{indoor}}}{C_{\text{source}}} = \frac{\left[\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right] \exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}}^{\text{eff}} \eta A_B} \right)}{\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}}^{\text{eff}} \eta A_B} \right) + \left[\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right] + \left[\frac{D_T^{\text{eff}} A_B}{Q_{\text{soil}} L_T} \right] \left(\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}}^{\text{eff}} \eta A_B} \right) - 1 \right)} \quad (1)$$

Here α is the vapor attenuation coefficient, and:

- A_B = surface area of enclosed space in contact with soil [m^2]
- $D_{\text{crack}}^{\text{eff}}$ = effective overall vapor-phase diffusion coefficient through the walls and foundation cracks [m^2/d]
- D_T^{eff} = effective overall vapor-phase diffusion coefficient between the source and foundation [m^2/d]
- L_{crack} = thickness of enclosed space walls and foundation [m]
- L_T = source - foundation separation [m]
- Q_B = enclosed space air exchange rate [m^3/d]
- Q_{soil} = soil gas flow rate into enclosed space due to under-pressurization [m^3/d]
- η = fraction of enclosed space surface area open for vapor intrusion [m^2/m^2]

Johnson and Ettinger (1991) discuss in detail the development of this equation, the significance of each parameter grouping, and the results for certain limiting cases. In brief, diffusion through the soil and foundation is characterized by the parameters D_T^{eff} , L_T , $D_{\text{crack}}^{\text{eff}}$, L_{crack} , A_B , and η . Advective flow of vapors from the soil, through the

foundation, and into the building is characterized by Q_{soil} , A_B , and η , and mixing within the enclosed space is characterized by Q_B and A_B .

The effective porous media overall vapor-phase diffusion coefficients are generally determined from the Millington-Quirk formulation (Millington 1959, Millington and Quirk 1961, Millington and Shearer 1971):

$$D^{\text{eff}} = D^{\text{air}} \frac{\theta_v^{3.33}}{\theta_T^2} + \left(\frac{D^{\text{H}_2\text{O}}}{H_i} \right) \frac{\theta_m^{3.33}}{\theta_T^2} \quad (2)$$

where:

H_i = Henry's Law constant [(mg/m³-vapor)/(mg/m³-H₂O)]

θ_m = volumetric moisture content [m³-H₂O/m³-soil]

θ_T = total porosity [m³-voids/m³-soil]

θ_v = volumetric vapor content [m³-vapor/m³-soil]

D^{air} = molecular diffusion coefficient in air [m²/d]

$D^{\text{H}_2\text{O}}$ = molecular diffusion coefficient in water [m²/d]

For reference, molecular diffusion coefficients in air for most petroleum fuel compounds range from 0.05 - 0.10 cm²/s (0.4 - 0.9 m²/d); molecular diffusion coefficients in water are roughly 1/10000 of molecular diffusion coefficients in air. USEPA (1996) tabulates relevant chemical properties such as D^{air} and D^{water} for many chemicals of interest. Total porosity varies roughly between 0.35 and 0.45 for most soil types; in many well-drained sandy soils, $\theta_m < \theta_T / 5$, θ_m can approach $\theta_T / 2$ in clayey soils, and θ_m approaches θ_T as depth increases through the capillary fringe to groundwater. More information on the parameterization of moisture levels through unsaturated soils and the capillary fringe in various soil types is presented in Guymon (1994).

In typical RBSL calculations, the source zone vapor concentration C_{source} [mg/m³] is often assumed to be related to the source zone total soil concentration C_T [mg/kg-soil], assuming a single-component, linear-partitioning relationships, and three-phase equilibrium (vapor, sorbed, dissolved phases):

$$C_T = \frac{C_{\text{source}} \theta_v}{\rho_b} \left[1 + \frac{\theta_m}{\theta_v H_i} + \frac{\rho_b K_s}{\theta_v H_i} \right] = \frac{C_{\text{source}} \theta_v}{\rho_b} R_v \quad (3)$$

where:

K_s = soil sorption coefficient [(mg/kg-soil)/(mg/m³-H₂O)]

R_v = soil vapor retardation factor [unitless]

ρ_b = soil bulk density [kg-soil/m³-soil]

While this expression is used frequently, it is not appropriate for cases where an immiscible phase is present (e.g., residual hydrocarbon source zones). In those cases the partitioning calculations are much more complex and generally nonlinear (Johnson *et al.* 1990). At high residual soil concentration levels (typically >500 mg/kg total hydrocarbons for gasoline; see Johnson *et al.* 1990), the partitioning is better approximated by Raoult's Law. Equation (3) may over- or under-predict the vapor concentration calculated using Raoult's Law.

As an example of the use of Equation (1), Figure 2 presents α vs. D_T^{eff}/L_T for the following reasonable parameter values:

A_B = 50 m²

Q_B = 1200 m³/d (12 air changes per day in 100 m³ enclosed space)

Q_{soil} = 1.5 m³/d (=1 L/min)

L_{crack} = 0.15 m

D_{crack} = 0.1 m²/d (cracks filled with well-drained sandy soil; note - the results are not sensitive to reasonable changes in this parameter for these conditions)

η = 0.001 m²/m² (note - the results are not sensitive to reasonable changes in this parameter for these conditions)

This graph allows examination of changes in attenuation with changes in distance from source (L_T) and effective diffusion coefficient (D_T^{eff}). For reference, moving along the x-axis in the direction of increasing D_T^{eff}/L_T corresponds to moving a source closer to the enclosed space, or alternatively, to increasing the effective diffusion coefficient (e.g., when decreasing the moisture content). As can be seen, no matter where the source is placed, or what the soil properties are, $\alpha < 10^{-3}$. The upper asymptote of $\alpha = 10^{-3}$ corresponds to the case where sources are very close to buildings, transport is controlled by advection through the foundation, and attenuation is due solely to dilution by mixing