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September 23, 2015

SUBMITTED VIA PADEP eCOMMENT

Technical Guidance Coordinator
Pennsylvania Department of Environmental Protection
Policy Office
Rachel Carson State Office Building
400 Market Street
Harrisburg, PA 17101

Re: Comments on Land Recycling Program Technical Guidance Manual for Vapor Intrusion into Buildings from Groundwater and Soil under Act 2

To Whom It May Concern:

We first wish to acknowledge the extensive effort by the Pennsylvania Department of Environmental Protection (DEP or Department) in drafting the Technical Guidance Manual for Vapor Intrusion into Buildings from Groundwater and Soil under Act 2 (Guidance). We would also like to acknowledge the Cleanup Standards Scientific Advisory Board and the core technical work group for their extensive work on the Guidance.

We appreciate the opportunity to submit comments on the Guidance to convey one specific technical comment (Comment #4) and otherwise to clarify the intent and scope. The below comments are those of the authors identified, based on input received from our expert consultant. The comments are not submitted as an official submission of the firm Fox Rothschild LLP or on behalf of any specific client of our firm.

Comment #1 -- Applicability

The guidance states that it is applicable "to any person or persons conducting a site remediation under Act 2." This statement may be too general. It seems likely to be intended to mean that this Guidance is applicable to any vapor intrusion evaluation that is otherwise required for an ongoing remediation under Act 2, for example under 25 Pa. Code Sections 250.312 or 250.404. In general the statement of applicability and the Guidance itself should be revised to more specifically state the applicability of this Guidance and for example, make clear the significance of this Guidance, if at all, to cleanups to the Background Standards, Special Industrial Area cleanups, storage tank corrective actions, and remediation for which final approval has been granted by the Department. In addition to this general comment, more specific comments are provided below.

Comment #1(a) Completed Clean-ups

The following statement could be misconstrued, "If a site characterization report has been submitted and approved by the Department prior to the effective date of this guidance, the remediator should update the VI evaluation portion of the report only." The Guidance should be clarified to make clear that this statement only applies where a final approval has not already been obtained from the Department.

Comment #1(b) Storage Tank Corrective Actions

It is not stated whether the Guidance is applicable to storage tank corrective actions, per Section 904c of Act 2. If the Guidance is intended to apply to storage tank corrective actions, this should be stated clearly.

Comment #1(c) Special Industrial Area cleanups

The Guidance notes that it applies to remediation performed under the Statewide Health Standard and Site-specific Standard. The Guidance does not refer to Special Industrial Area (SIA) cleanups. Does this mean that the Guidance does not need to be followed for SIA cleanups? It should be made clear in the Guidance whether the risk of vapor intrusion is something that the Department considers to potentially present "an immediate, direct or imminent threat" that would prevent a property from being occupied for its intended purpose. For example, in the past, if an SIA site had contaminated groundwater, the SIA agreement would note that and remediation would not be necessary if that site was on public water, regardless of the levels of contamination in the groundwater. Are economic development agencies and redevelopment authorities that take on SIA sites now going to need to do vapor assessments? If so, is this Guidance intended to provide the procedures and standards that should be used? Under what circumstances will an economic development agency or redevelopment authority have to install sub-slab depressurization systems in old industrial

buildings in order for them to be put back into productive reuse? In some cases, for large older buildings (200,000 square feet or more), the cost of such a system could be more than the amount of grant money made available through the Pennsylvania Department of Community & Economic Development.

Comment #2 – Environmental Covenants

The Guidance should be revised throughout to specify that an environmental covenant is needed only if maintenance of engineering and institutional controls is required to demonstrate attainment of an Act 2 remediation standard. In that regard, the Guidance should note that clean-ups that otherwise meet the Statewide Health Standard or Site-Specific Standards, but voluntarily install sub-slab depressurization or radon-like mitigation systems as an added protection measure, do not need to include continued operation and maintenance of that system in an environmental covenant. For example, a buyer and seller in the context of a transaction may agree that closing is conditioned on the seller obtaining a letter from DEP approving an Act 2 Final Report. Those same parties may also agree that the seller must install a sub-slab depressurization or radon-like mitigation system prior to closing, as a term or condition of the transaction. However, unless that system is required to attain or maintain an Act 2 standard, an environmental covenant should not be required.

Comments #3 – Definition of "Potential VI Source"

With regard to the Definition of "Potential VI source," the Guidance should clarify that "contamination" as used in the Guidance means the level of contamination found at the property that currently exists, and not the level of contamination that may have existed prior to any remediation of the soil and/or groundwater. The statewide health standard, which is discussed in Section 301(a)(2) of Act 2, is the standard adopted by the EQB to achieve a uniform health-based cleanup level that addresses any substantial "present" or "probable future risk" to human health and the environment. It would be helpful if the Guidance clearly explained that the level of contamination that may have been present at a site prior to remediation need not be taken into consideration in performing a VI investigation, because the Act 2 Statewide health standard deals with "present" or "probable future risk" and not risks posed by sources that have been remediated.

Comment #4 – Regarding use of Soil Vapor Intrusion Modeling

The Guidance provides for the use of soil vapor intrusion models to simulate indoor air quality in buildings using site-specific geologic data, building construction information, and concentrations of volatile organic compounds (VOCs) in soil, groundwater, or "near-source" soil gas. Soil vapor intrusion modeling is to be performed using Johnson and Ettinger (1991) spreadsheet models published by USEPA (2004) with a combination of site-specific and PADEP-specified input parameters to demonstrate attainment of a site-specific standard, or, on a more limited

basis, the Statewide health standard. The Guidance prohibits the use of soil vapor intrusion models for scenarios where "preferential pathways" exist within five feet of a building foundation. Legitimate preferential pathways, such as open wells or other high-permeability conduits, violate the assumptions inherent in the Johnson and Ettinger models by allowing VOCs to enter or come into contact with a structure through processes other than diffusive flux through the soil column.

The Guidance incorrectly identifies a dirt basement floor as a preferential pathway. However, in the absence of legitimate preferential pathways, a dirt basement floor scenario is an ideal application for the Johnson and Ettinger models, is one that is easily simulated using the USEPA spreadsheet tools, and is described in the original peer reviewed publication by Johnson and Ettinger (1991) – see *Attachment A.*

The USEPA versions of the Johnson and Ettinger model calculate the rates at which VOCs will migrate into a building based on two processes:

1) The upward flux of VOCs from a source (groundwater, soil, or near source soil-gas) to the bottom of a structure is controlled by upward molecular *diffusion* of VOCs from the source through the vadose zone. In diffusive flux, VOC molecules migrate upward through stagnant soil gas along a concentration gradient. The model uses this process to determine the total supply of VOC vapors to the zone immediately below the structure and is not influenced by the type of structure (basement versus slab-on-grade) or construction of the structure (e.g., the quantity or size of cracks in the concrete floor or absence of a concrete floor).

2) The flux of VOCs into the structure from the area immediately beneath the structure is controlled by *advection*, or the physical movement of soil gas as it is "swept" into the building through cracks in the floor slab or foundation. Advection, in turn, is controlled by the pressure differential between the structure and surrounding soil gas, and the total area of cracks in the concrete floor slab separating the structure from the underlying soil. This process cannot deliver VOCs into the structure at a rate greater than VOCs diffuse upward from the source via the first process described above. In most scenarios, this advection term significantly reduces the predicted rate of VOC migration into a structure in comparison to a 'diffusion only' scenario.

Modeling of the first process described above – upward diffusion of VOCs through the vadose zone without advection – can be directly supported by data collected in the field during a remedial investigation, including vadose zone soil type(s), depth to groundwater, and VOC concentrations in groundwater, soil, or near-source soil gas samples. Modeling of the second process – advection of soil gas from the sub-slab zone into the structure – requires additional input parameters that often must be assumed and are not easily measured or verified in the field,

e.g., the aperture of cracks in a concrete floor slab and the pressure differential between the sub-slab zone and interior space.

Equation (19) in the original publication by Johnson and Ettinger (1991) – see *Attachment A* – addresses the dirt basement floor scenario by assuming that the flooring and wall materials do not provide any impediment to soil vapor migration, thereby eliminating the pressure differential and limiting advection to zero, and allowing all contaminant mass diffusing upward from the source to enter the structure. Eliminating the advection term from the model increases predicted soil vapor migration into the structure to the maximum rate controlled by the diffusion process.

A dirt basement floor scenario is easily simulated using the USEPA Johnson and Ettinger advanced spreadsheet models by setting the floor slab thickness to zero and eliminating the advection term described above, effectively implementing Equation (19) of Johnson and Ettinger (1991) . By doing so, the model increases the predicted flux of VOCs into the structure and produces results that are both scientifically sound and conservatively protective of human health.

Thank you again to the Department and the CSSAB for their work on this important topic and for this opportunity to provide comment

Very truly yours,

Christopher M. Roe

Victoria W. Hollinger

CMR/stj

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

Attachment A

Johnson, P.C. and Ettinger, R.A (Johnson and Ettinger, 1991). "Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings." Environmental Science and Technology, Vol. 25, No. 8, 1991. p. 1445-1452.

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

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

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■ The intrusion into and subsequent accumulation of contaminant vapors in buildings and family dwellings is of concern for health and safety reasons. When preparing environmental and health risk assessments, one must be able to quantify this exposure pathway in order to decide if site-specific conditions correspond to unacceptable indoor contaminant vapor concentrations. For cases in which contaminated-site soil cleanup levels can be negotiated based on site-specific conditions, a related problem is the determination of residual contaminant levels below which associated adverse health effect risks are deemed negligible. Unfortunately, there are currently no accepted models for predicting vapor intrusion rates, and there is considerable debate over which transport mechanisms govern the process. This paper presents a heuristic model for screening-level calculations. It incorporates both convective and diffusive mechanisms, as well as contaminant soil, and building foundation properties. Sample calculations are presented for a range of parameter values to illustrate use of the model and the relative contributions of individual transport mechanisms.

Introduction

The intrusion and subsequent accumulation of radon vapors in commercial buildings and family dwellings has received considerable attention in the last decade. Of growing interest is the related problem of vapor transport from contaminated soils into buildings and dwellings. When preparing health and environmental risk assessments, regulators may require one to determine a residual contaminant level below which the associated adverse health effect risk is deemed negligible. To accomplish this, however, predictive transport models are required. Despite the attention focused on radon intrusion, no such validated models are available.

The current level of understanding is that both diffusion and convection contribute to vapor intrusion, and specific site characteristics will determine the significance of each. Nazaroff et al. (*1*) attempted to correlate radon concentrations in basements with building ambient pressure differences, wind speed, temperature differences, soil radon activity, and indoor air-exchange rates. In summary, for the three dwellings studied, typical building underpressurizations (ambient basement pressure drop) ranged between 1 and 50 Pa, and radon intrusion rates increased with increasing building underpressurization. Through the use of a tracer gas and controlled building underpressurization, Nazaroff et al. (*2*) studied the coupling between building underpressurization, induced soil depressurization, and flow of soil gas to a building. In another field study, Hodgson et al. (*3*) studied the transport of vapors from a landfill to a residential basement; they concluded that convective transport was negligible for the conditions at that site. By building a scale model of a building, Arnold (*4*) attempted to correlate building underpressurization, wind speed, soil type, soil gas intrusion rates, and pressure distributions in surrounding soils.

Attempts to model radon intrusion have produced both semianalytical solutions and detailed numerical codes. Landman (*5*), who considered only vapor-phase diffusion, modeled radon transport through cracks in slabs and predicted that a slab with 1% open cracks by area will reduce the radon flux by 75% relative to the case of a bare dirt floor. Landman and Cohen (*6*) later tried to simplify this analysis and incorporate convective transport. Other authors, such as Zapalac (*7*), have attempted to model and measure radon fluxes through intact (i.e., no macroscopic cracks) concrete barriers.

Recently, numerical models have been employed by Garbesi and Sextro (*8*) and Loureiro et al. (*9*). The former model soil gas entry through "permeable" walls, rather than through cracks and openings, and predict reasonable soil gas entry rates for the cases studied. The latter couple soil gas flow field solutions with a contaminant transport model to predict radon intrusion rates through cracks and openings in basement floors and walls. It should be noted that one must be careful when extending results and conclusions from radon intrusion studies to the problem addressed in this study. In the case of radon intrusion, vapors are typically generated within the soil matrix adjacent to the foundation, while contaminant vapors of the type discussed in this report must migrate from a source located a distance from the building.

The goal of this work is similar to those of Nazaroff (*10*) and Nazaroff and Sextro (*11*); we want to develop a less computationally complex screening-level model for estimating contaminant vapor intrusion rates. Nazaroff (*10*) outlined a semianalytical approach for predicting indoor radon concentrations in the limit of convective-dominated transport, while Nazaroff and Sextro (*11*) described a more empirical technique based on a site-specific in situ measurement. Here we utilize the results and observations of these authors to formulate a heuristic model for predicting the intrusion rate of contaminant vapors into buildings through foundations in a more general scenario: contaminant vapors originating an arbitrary distance away from a building. This model can be used as a risk assessment screening-level tool; it can be used to identify sites, or contaminant levels, for which contaminant exposures through a vapor inhalation pathway may cause adverse health effects. It can also be used as a tool to help identify sites where more detailed numerical simulations or field sampling are appropriate. Below, the basis for the model is discussed, model equations are derived, and sample calculations are presented that illustrate the use of the model.

Heuristic Model Basis

While the formal development of the heuristic model is presented below, it is necessary to identify relevant phenomena that govern contaminant vapor transport into dwellings. In the following section, a dimensional analysis is conducted to assess the relative importance of each phenomenon. The transport of contaminants through soil matrices is often modeled by solving the following transport equation:

$$\frac{\partial \sum_i \epsilon_i C_i}{\partial t} + \sum_i \mathbf{u}_i \cdot \nabla C_i = \sum_i \nabla \cdot D_i^{\mathrm{eff}} \nabla C_i + \sum_i R_i \qquad (1)$$

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where i is a subscript that specifies the phase (i.e., v = vapor, s = sorbed, f = free phase or precipitate, and m = soil moisture), t is time (s), ϵ_i is the volume fraction of phase i (volume of phase i/volume of soil, dimensionless), C_i is the concentration of contaminant in phase i (mass/volume of phase i, g/cm^3), $\mathbf{u}_i$ is the Darcy velocity vector associated with phase i (cm/s), ∇ is the del operator (1/cm), D_i^{eff} is the effective porous medium diffusion coefficient of contaminant in phase i (cm^2/s), and R_i is the formation rate of contaminant in phase i (g/cm^3-s).

For the special case where residual contaminant levels are low enough that no contaminant free-liquid/precipitate phase is present in the soil pores, under equilibrium conditions contaminant levels in the vapor, sorbed, and soil moisture phases are often assumed to be proportional to each other and the total contaminant level [Johnson et al. (*12*)]. Equation 1 can then be written in terms of a single phase concentration. One can assume, without any loss of generality, that contaminant levels in the soil moisture and vapor phases are related by a Henry's law constant, H (cm^3 of H_2O/cm^3 of vapor):

$$C_v = HC_m \tag{2}$$

A similar equation can be written for the relationship between sorbed and soil moisture phases, except that H is replaced by a sorption coefficient. If one assumes that diffusive transport is significant only in the vapor and soil moisture phases, then it follows from eq 2 that

$$\sum_i \nabla\cdot D_i^{\text{eff}}\nabla C_i = \nabla\cdot(D_v^{\text{eff}} + D_m^{\text{eff}}/H)\nabla C_v = \nabla\cdot D^{\text{eff}}\nabla C_v \tag{3}$$

where D^{eff}, defined by eq 3, is the "effective porous medium diffusion coefficient based on vapor-phase concentrations". The effective porous medium diffusion coefficients (D_m^{eff} and D_v^{eff}) are related to the pure component molecular diffusivities in water and air, D^{H_2O} and D^{air}, total soil porosity, $\epsilon_T = (\epsilon_v + \epsilon_m)$, vapor-filled porosity, ϵ_v, and moisture-filled porosity, ϵ_m, by the Millington–Quirk [Bruell and Hoag (*13*)] expression:

$$D_m^{\text{eff}} = D^{H_2O}\epsilon_m^{3.33}/\epsilon_T^2 \tag{4}$$

and

$$D_v^{\text{eff}} = D^{\text{air}}\epsilon_v^{3.33}/\epsilon_T^2 \tag{5}$$

where ϵ_m and ϵ_v are related to ϵ_T, the moisture content θ_m (cm^3 of H_2O/g of soil), and the bulk soil density ρ_b (g/cm^3):

$$\epsilon_m = \theta_m\rho_b \tag{6}$$

and

$$\epsilon_v = \epsilon_T - \theta_m\rho_b \tag{7}$$

For most compounds (except those with very small Henry's law constants), the contribution due to diffusion through the soil moisture will be insignificant in comparison with vapor-phase diffusion.

For the purpose of this analysis, we also assume that significant convective transport occurs only in the vapor phase, and vapor flow is described by Darcy's law:

$$\mathbf{u}_v = -\frac{k_v}{\mu}\nabla P \tag{8}$$

where k_v is the soil permeability to vapor flow (cm^2), μ is the vapor viscosity (g/cm·s), P is the pressure in the vapor phase (g/cm·s^2), and $\mathbf{u}_v$ is the vapor-phase mass-average velocity (cm/s).

Table I. Dependence of Pe on Soil Type[a]

soil type	permeability, k_v (darcy or 10^{-8} cm^2)	Pe
silt	0.01–0.1	0.08–0.08
silty sand	0.1–1	0.08–0.8
fine sand	1–10	0.8–8
medium sand	10–100	8–80

[a] Pe = $(k_v\Delta P_r L_D/D^{\text{eff}}\mu L_P)$, where ΔP_r = 10 Pa = 100 g/cm·s^2 = 10^{-4} atm, D^{air} = 0.087 cm^2/s (benzene at 20 °C); $D^{H_2O} = 1.0 \times 10^{-5}$ cm^2/s; H = 0.18 cm^3 of H_2O/cm^3 of vapor (benzene at 20 °C); ϵ_T = 0.38; θ_m = 0.07 g of H_2O/g of soil (sandy soil at field capacity moisture content); ρ_b = 1.7 g of soil/cm^3 of soil; $\mu = 1.8 \times 10^{-4}$ g/cm·s; $L_D = L_P$; $D^{\text{eff}} \approx D_v^{\text{eff}}$ = 0.087 cm^2/s × $(0.26^{3.33}/0.38^2)$ = 6.8 × 10^{-3} cm^2/s.

Inserting eqs 3 and 8 into eq 1 and nondimensionalizing the resulting equation yields

$$\frac{\partial\sum_i \epsilon_i C_i^*}{\partial t^*} - \left(\frac{L_P}{L_D}\right)(\nabla^* P^*)\cdot(\nabla^* C_v^*) = \nabla^*\cdot\left[\frac{D^{\text{eff}}\mu L_P}{k_v\Delta P_r L_D}\right]\nabla^* C_v^* + \sum_i R_i^* \tag{9}$$

where ΔP_r is the reference or characteristic indoor–outdoor pressure difference and * denotes nondimensional variables:

$$C_i^* = C_i/C_r \qquad \nabla^* = L_D\nabla \qquad P^* = P/\Delta P_r$$
$$t^* = t(k_v\Delta P_r/L_P L_D\mu) \qquad R_i^* = R_i L_P L_D\mu/C_r k_v\Delta P_r$$

where C_r, L_D, and L_P are characteristic concentration, diffusion pathway length, and convection pathway length values, respectively, chosen to give the dependent concentration variable and derivatives of C_i^* and P^* magnitudes of order unity. Then the dimensionless group

$$[k_v\Delta P_r L_D/D^{\text{eff}}\mu L_P] = \text{Pe} \tag{10}$$

determines the relative significance of convective and diffusive transport mechanisms. Here Pe is the Peclet number, expressed in terms of the driving pressure ΔP_r. If Pe $\gg$ 1, convective transport dominates; if Pe $\ll$ 1, diffusive transport dominates. Note that the Peclet number defined by eq 10 contains two length scales L_D and L_P. This is appropriate for the problem of contaminant vapor intrusion into buildings, where the characteristic length scales for diffusion and convection may be quite different. Logical choices for L_D and L_P are the contaminant source–basement separation and the distance between ground surface and the basement floor, respectively.

It is useful to examine the magnitude of Pe before formulating any simpler vapor intrusion models. Based on the Nazaroff et al. (*1, 2*) studies, typical values of ΔP_r are 1–10 Pa (10–100 g/cm·s^2), so we will choose the following representative parameter values: ΔP_r = 10 Pa = 100 g/cm·s^2 = 10^{-4} atm; D^{air} = 0.087 cm^2/s (benzene at 20 °C); $D^{H_2O} = 1.0 \times 10^{-5}$ cm^2/s; H = 0.18 cm^3 of H_2O/cm^3 of vapor (benzene at 20 °C); ϵ_T = 0.38; θ_m = 0.07 g of H_2O/g of soil (sandy soil at field capacity moisture content); ρ_b = 1.7 g of soil/cm^3 of soil; $\mu = 1.8 \times 10^{-4}$ g/cm·s; $L_D = L_P$. Table I presents values for Pe for different soil types. While θ_m, ϵ_T, ρ_b, and hence D^{eff} will vary with soil type, it has been assumed that all soils listed in Table I have similar total porosities, soil moisture contents, and bulk densities (an assumption that would not be valid for comparing sandy and clayey soils). The diffusion coefficients in water and air are also compound-specific; however, compounds whose molecular weights range from 70 to 300 have diffusion coefficients that differ by only a factor of ~2 [Lyman et al. (*14*)]. Of the parameters appearing in eq 10, the soil

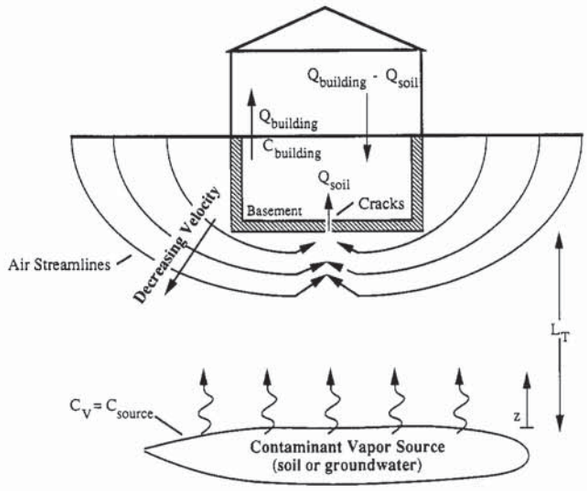

Figure 1. Vapor intrusion scenario.

permeability, k_v, is the most variable at any given site; it is not unusual for k_v to vary by 3 orders of magnitude across a site the size of a typical residential lot. As can be seen in Table I, Pe ranges between 0.01 and 100 for the soil types listed there. The significance of this observation is that any vapor intrusion model based only on either convective or diffusive transport mechanisms cannot reasonably describe the relevant phenomena over the typical range of soil types. Any proposed model, therefore, must include both transport mechanisms.

Formulation of the Heuristic Model

This discussion will be limited to problems in which chemical or biological transformations are not significant (i.e., $R_i = 0$). Recall that the goal of this development is to produce a predictive model suitable for screening-level calculations. Given that biological transformations in the unsaturated zone are presently not very well understood, it is not appropriate to attempt to incorporate them into this level of modeling. The reader should understand, however, that degradation due to microorganisms does occur; any model that includes them will predict lower intrusion rates than the model presented here (unless the contaminant of concern is produced by the biological transformation).

At this point we will restrict the analysis to steady-state (nondiminishing source) problems, although it will be shown later how one might adapt the results to diminishing source problems. Figure 1 presents a simplified sketch of the problem under consideration, in which a contaminant vapor source of concentration C_{source} is located some distance L_T below the floor of a basement or building slab. We want to predict the intrusion rate of vapors into the building. To accomplish this, the following assumptions are made:

(i) Contaminant vapors enter structures primarily through cracks and openings in the walls and foundation (electrical outlets, wall–floor seams, sump drains, etc.).

(ii) Convective transport is likely to be most significant in the region very close to a basement, or foundation, and vapor velocities decrease rapidly with increasing distance from a structure.

(iii) Vapor-phase diffusion is the dominant mechanism for transporting contaminant vapors from contaminant sources located away from the foundation to the soil region near the foundation.

(iv) All contaminant vapors originating from directly below the basement will enter the basement, unless the floor and walls are perfect vapor barriers.

Assumption i reflects the current thinking that vapor intrusion is mainly due to cracks, seams, and openings in basement floors and walls, while ii and iii are based on the analysis presented above, the Peclet numbers appearing in Table I, and analogy to known solutions of fluid mechanics problems. In this simplistic model, contaminants volatilize from the source and diffuse toward the foundation. When convection is significant, they are "swept" into the building through cracks; otherwise, the contaminant vapors diffuse through the cracks and openings. Assumption iv restricts contaminant vapors from leaking around a building to ground surface and, therefore, adds a level of conservation to the model. Vapor leakage to the surface will be significant whenever the resistance to transport into a building is much greater than the resistance to transport to ground surface, such as buildings built on relatively intact slab foundations. It should be noted that the final results will not be limited by the validity of assumption i; if one follows the analysis below for the case where vapors are transported through intact porous walls, the final equations are identical in form with the results presented below (this will be shown later).

In addition to assumptions i–iv listed above, there are also assumptions inherent in the simplistic mathematical models described below. One-dimensional transport models form the basis for the heuristic model; therefore, it is assumed that the soil is homogeneous within any horizontal plane with respect to effective diffusion coefficients (heterogeneity in the vertical direction is accounted for). Also, it is assumed that convective vapor flow in the region near the foundation is uniform. This assumption, however, does not preclude application of the model to scenarios where there is a uniform layer of gravel adjacent to the foundation; in fact, the idealization described in assumption ii accurately represents this scenario, and one only needs to be sure to predict the soil gas entry rate based on properties of this region (and not the permeability of surrounding soils).

In the following, the heuristic vapor intrusion model is formulated by combining approximate mathematical descriptions of the relevant transport phenomena:

(a) Diffusive Transport from the Source to a Region near the Structure. As described above, it is assumed that contaminant vapors are transported from the contaminant source to a region near the structure, primarily by a molecular diffusion through pore vapor and soil moisture phases. The rate can be approximated by the expression

$$E_1 = A_B\,(C_{source} - C_{soil})D_T^{eff}/L_T \qquad (11)$$

where E_1 is the mass-transport rate toward the structure (g/s), A_B is the cross-sectional area through which vapors pass (cm^2), C_{source} is the vapor concentration at the contaminant source (g/cm^3), C_{soil} is the vapor concentration in the region near the structure (g/cm^3), L_T is the distance from contaminant source to foundation (cm), and D_T^{eff} is the "overall" effective porous media diffusion coefficient based on vapor-phase concentrations for the region between the source and foundation (cm^2/s).

The cross-sectional area, A_B, can be approximated by the total basement area (floor and walls). Assuming that convection, when significant, is only dominant in a region very near the foundation allows us to approximate the total diffusion length, L_T, as the distance between the source and foundation. The soil permeability to vapor flow, building underpressurization, and physical setting will determine the actual thickness of the convection-dominated region, which will increase with increasing permea-

bility to vapor flow and increased building underpressurization. In general, the unsaturated soil zone may be composed of several soil types with varying moisture contents and porosities, and the effective overall diffusion coefficient for a region between $z = 0$ and $z = L_T$ is

$$D_T^{eff}/L_T = \left[\int_0^{L_T} dz/D^{eff}(z)\right]^{-1} \quad (12)$$

where $D^{eff}(z)$ is the effective porous media diffusion coefficient at z, which is a function of the contaminant type and soil characteristics as defined by eqs 3–7.

For systems composed of n distinct soil layers defined by thicknesses L_i and uniform effective overall porous media diffusion coefficients D_i^{eff}, eq 12 reduces to

$$D_T^{eff}/L_T = [\sum_{i=0}^{n} L_i/D_i^{eff}]^{-1} \quad (13)$$

(b) Transport from Soil Gas into Building. The transport of contaminants from soil gas adjacent to a foundation is assumed to occur by a combination of convective and diffusive transport mechanisms. As a first approximation, the steady-state, one-dimensional solution to eq 9 for vapor transport through a crack (or porous medium) with a constant uniform convective velocity (Q_{soil}/A_{crack}) is used to predict the total rate of contaminant intrusion into a building:

$$E = Q_{soil}C_{soil} - \frac{Q_{soil}(C_{soil} - C_{building})}{[1 - \exp(Q_{soil}L_{crack}/D^{crack}A_{crack})]} \quad (14)$$

where E is the entry rate of contaminant into the building (g/s), Q_{soil} is the volumetric flow rate of soil gas into the building (cm^3/s), D^{crack} is the effective vapor-pressure diffusion coefficient through the crack (cm^2/s), L_{crack} is the thickness of the foundation (cm), $C_{building}$ is the contaminant vapor concentration in the building (g/cm^3), and A_{crack} is the area of cracks/openings through which contaminant vapors enter the building (cm^2).

The only "unknown" in eqs 11 and 14 is the soil gas contaminant concentration, C_{soil}, which can be obtained by requiring that the rates E_1 and E be equal at steady state. The result

$$C_{soil} = \left[C_{source}\left[\frac{D_T^{eff}A_B}{Q_{soil}L_T}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - 1\right] + C_{building}\right] \Big/ \left[\left[\frac{D_T^{eff}A_B}{Q_{soil}L_T}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - 1\right] + \exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right)\right] \quad (15)$$

can be substituted into eq 14 to obtain E, the rate of contaminant entry into a building through the foundation:

$$E = \left[\frac{D_T^{eff}A_B C_{source}}{L_T}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - \left[\frac{C_{building}}{C_{source}}\right]\right] \Big/ \left[\left[\frac{D_T^{eff}A_B}{Q_{soil}L_T}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - 1\right] + \exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right)\right] \quad (16)$$

When eq 16 is written this way, E is the product of the steady-state diffusive rate of contaminant transport from a source to a bare dirt floor foundation (first term on right-hand side) and a factor containing a number of dimensionless groups whose significance will be discussed below.

Indoor Air Quality. Equation 16 can be incorporated into a steady-state mass balance for a basement (or building) to produce an explicit expression for the indoor contaminant vapor. Assuming no other contaminant sources or sinks (i.e., sorption to walls or furniture) and a well-mixed building, this expression can be written

$$Q_{building}C_{building} = E \quad (17)$$

where $Q_{building}$ denotes the basement (or building) ventilation rate, expressed as a volumetric flow rate. Often, this term is expressed as the product of an "air-exchange rate" and a basement (or building) volume; however, here these terms are combined into $Q_{building}$. Substituting eq 16 into eq 17 and rearranging yields

$$C_{building} = \left[C^*_{building} \times \exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right)\right] \Big/ \left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) + \left[\frac{D_T^{eff}A_B}{Q_{building}L_T}\right] + \left[\frac{D_T^{eff}A_B}{Q_{soil}L_T}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - 1\right]\right] \quad (18)$$

where

$$C^*_{building} = \left[\frac{D_T^{eff}A_B C_{source}}{Q_{building}L_T}\right] \quad (19)$$

In eqs 18 and 19, $C^*_{building}$ represents the indoor vapor concentration corresponding to the case where vapors diffuse from the source to a bare soil foundation. As will be derived later, this is the limiting case in which Q_{soil} becomes very small and the diffusional resistance through the basement floors/walls is significantly less than the diffusional resistance through the soil zone between the contaminant vapor source and building. Equation 18 can also be arranged to produce the "attenuation coefficient" α:

$$\alpha = C_{building}/C_{source} \quad (20)$$

or equivalently

$$\alpha = \left[\left[\frac{D_T^{eff}A_B}{Q_{building}L_T}\right] \times \exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right)\right] \Big/ \left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) + \left[\frac{D_T^{eff}A_B}{Q_{building}L_T}\right] + \left[\frac{D_T^{eff}A_B}{Q_{soil}L_T}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - 1\right]\right] \quad (21)$$

Both eqs 18 and 21 depend on three dimensionless groups:

$$\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}} \qquad \frac{D_T^{eff}A_B}{Q_{building}L_T} \qquad \frac{Q_{soil}}{Q_{building}}$$

The first represents the equivalent Peclet number for transport through the foundation, the second is the attenuation coefficient (as defined in eq 20) for diffusion-dominated transport from a constant source to a bare dirt floor, and the third is the attenuation coefficient for con-

vective transport from a source located adjacent to the building.

At this point it is useful to examine the behavior predicted by eq 21 in certain limiting situations, in order to verify that the mathematics represents the phenomena incorporated into their derivation and that the results fall within appropriate bounds:

(a) $(Q_{soil}L_{crack}/D^{crack}A_{crack}) \rightarrow \infty$. In this limit convection is the dominant transport mechanism through the basement (building) floor and walls. Equation 21 becomes

$$\lim \frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}} \rightarrow \infty \qquad \alpha \rightarrow \frac{\left[\dfrac{D_T^{eff}A_B}{Q_{building}L_T}\right]}{\left[\dfrac{D_T^{eff}A_B}{Q_{soil}L_T}\right] + 1} \tag{22}$$

If the source lies directly beneath the foundation ($L_T \rightarrow 0$), then $\alpha \rightarrow Q_{soil}/Q_{building}$, which is the proper result for convection-dominated transport of a vapor stream with concentration C_{source}. If the source is "far" from the basement (i.e., $D_T^{eff}A_B/Q_{soil}L_T \rightarrow 0$), then transport is limited by diffusion from the source to foundation, and $\alpha \rightarrow D_T^{eff}A_B/Q_{building}L_T$. Note that in the limit $Q_{soil}L_{crack}/D^{crack}A_{crack} \rightarrow \infty$ the results are independent of the cracked area of the floor and walls. This is because contaminant vapors are swept into the building as fast as they are transported to the soil adjacent to the floor and walls.

(b) $(Q_{soil}L_{crack}/D^{crack}A_{crack}) \rightarrow 0$. In this limit diffusion is the dominant transport mechanism through the basement floor and walls, and eq 21 reduces to

$$\lim \frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}} \rightarrow 0$$

$$\alpha \rightarrow \frac{\left[\dfrac{D_T^{eff}A_B}{Q_{building}L_T}\right]}{1 + \left[\dfrac{D_T^{eff}A_B}{Q_{building}L_T}\right] + \left[\dfrac{D_T^{eff}A_BL_{crack}}{D^{crack}A_{crack}L_T}\right]} \tag{23}$$

Equation 23 contains two dimensionless groups. As discussed above, $D_T^{eff}A_B/Q_{building}L_T$ represents the attenuation coefficient for diffusive transport to a bare dirt floor. The second dimensionless group, $D_T^{eff}A_BL_{crack}/D^{crack}A_{crack}L_T$, is a measure of the diffusion rates through the soil relative to those through the floor and walls. If $D_T^{eff}A_BL_{crack}/D^{crack}A_{crack}L_T \ll 1$, then $\alpha \rightarrow D_T^{eff}A_B/Q_{building}L_T$ because $D_T^{eff}A_B/Q_{building}L_T$ will typically be much less than unity unless $Q_{building} \rightarrow 0$. If $D_T^{eff}A_BL_{crack}/D^{crack}A_{crack}L_T \gg 1$, then $\alpha \rightarrow D^{crack}A_{crack}/Q_{building}L_{crack}$, which is the appropriate attenuation coefficient for transport from a source located adjacent to the floor and walls. When $D_T^{eff}A_BL_{crack}/D^{crack}A_{crack}L_T \gg 1$, then diffusion through the floor and walls is the rate limiting mechanism, and there is a vapor concentration "buildup" below the building or basement.

(c) $Q_{building} \rightarrow 0$. This limit corresponds to a perfectly sealed basement, Q_{soil} must also approach zero, and the model predicts that $\alpha \rightarrow 1$; that is, the indoor contaminant vapor concentration approaches the contaminant vapor concentration in the soil gas.

Sample Calculations

On the basis of the analysis above, it appears that model predictions fall correctly within the appropriate bounds for all limiting cases examined. These results, however, give no indication of what "typical" values of these dimensionless groups might be. It is useful at this point, therefore, to examine model predictions for a sample case. Consider a 10 m × 7 m × 3 m (length × width × height) basement whose floor lies 2 m below grade. It is assumed that the floor/wall cracks and openings are filled with dust and dirt characterized by a density, porosity, and moisture content similar to that of the underlying soil. Model parameters A_B, L_{crack}, $Q_{building}$, D^{air}, D^{H_2O}, H, θ_m, ϵ_T, and ρ_b are given in Table II. The remaining unspecified parameters are the convective flow rate from the soil into the basement, Q_{soil}, the area of cracks, A_{crack}, and the distance between the contaminant source and the foundation, L_T. The soil gas flow rate, Q_{soil}, is likely to be dependent on the basement crack area, A_{crack}, soil type and stratigraphy, building underpressurization, and basement geometry. For simplicity, however, we will estimate Q_{soil} as suggested by Nazaroff (*10*):

Table II. Parameter Values Used To Generate Figures 2–5

A_B = 7 m × 10 m + 2(2 m × 7 m) + 2(2 m × 10 m) = 138 m² = 138 × 10⁴ cm²
L_{crack} = 6 in. = 15 cm
$Q_{building}$ = 7 m × 10 m × 3 m × 0.5 volume exchanges/h = 105 m³/h = 2.9 × 10⁴ cm³/s
D^{air} = 0.087 cm²/s (benzene)
D^{H_2O} = 1.0 × 10⁻⁵ cm²/s
H = 0.18 cm³ of H_2O/cm³ of air (benzene)
θ_m = 0.07 g of H_2O/g of soil
ϵ_T = 0.38 cm³/cm³ of soil
ρ_b = 1.7 g/cm³
ΔP = 1.0 Pa = 10 g/cm·s²

$$Q_{soil} = \frac{2\pi\Delta P k_v X_{crack}}{\mu \ln [2Z_{crack}/r_{crack}]} \qquad \frac{r_{crack}}{Z_{crack}} \ll 1 \tag{24}$$

Equation 24 is an analytical solution for flow to a cylinder of length X_{crack} and radius r_{crack} located a depth Z_{crack} below ground surface; this is an idealized model for soil gas flow to cracks located at floor/wall seams. Here ΔP, k_v, and μ are as defined above. For this sample problem, Z_{crack} = 2 m (as stated above), X_{crack} is taken to be the total floor/wall seam perimeter distance (34 m), and for consistency r_{crack} is given by

$$r_{crack} = \eta A_B/X_{crack} \tag{25}$$

where the ratio $\eta = A_{crack}/A_B$, so that $0 \leq \eta \leq 1$. For reference, $\eta = 0.01$ corresponds to r_{crack} = 4.1 cm for the values of A_B and X_{crack} given above; r_{crack} = 1 cm corresponds to $\eta = 0.0025$.

In the Nazaroff et al. studies (*1, 2*), estimates for Q_{soil} are in the 280–2800 cm³/s (1–10 m³/h) range, for induced building underpressurizations of 5–30 Pa and very permeable soils ($k_v > 10^{-8}$ cm²). Note that 1 m³/h corresponds to ~1% of the assumed total basement air exchange rate (0.5/h). For the purpose of this sample calculation we choose ΔP = 1 Pa (10 g/cm·s²), which is probably a reasonable long-term average value for screening calculations.

Figure 2 presents soil gas flow rates predicted by eq 24 for $\eta = 0.01$ and $\eta = 0.001$. This figure illustrates the strong dependence of Q_{soil} on soil type, and a weaker dependence on crack size (as reflected in the value of η). For very permeable soils ($k_v \geq 10^{-6}$ cm²), the predicted Q_{soil} values are of the same order of magnitude as the values observed by Nazaroff (*1, 2*). For example, Q_{soil} = 260 cm³/s for $\eta = 0.01$ and $k_v = 1 \times 10^{-6}$ cm². For reference, medium sandy soils correspond to $10^{-7} < k_v < 10^{-6}$ cm².

Figures 3–5 present predicted attenuation coefficients α, for $\eta = 0.01$, and $\eta = 0.001$, as a function of k_v, for L_T

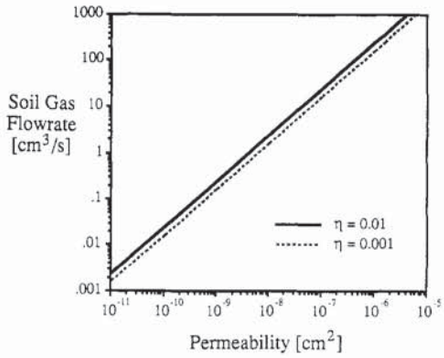

Figure 2. Dependence of soil gas entry flow rates, Q_{soil}, on soil permeability, k_v, as predicted by eq 24 for the parameters listed in Table II.

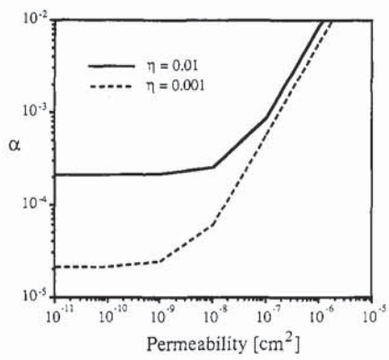

Figure 3. Dependence of attenuation coefficient, α, on soil permeability, k_v, as predicted by eq 21 for the parameters listed in Table II and $L_T = 0$.

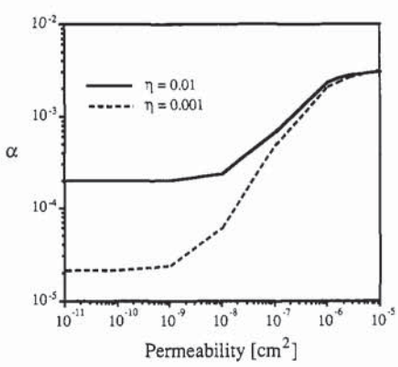

Figure 4. Dependence of attenuation coefficient, α, on soil permeability, k_v, as predicted by eq 21 for the parameters listed in Table II and $L_T = 100$ cm.

= 0, 100, and 1000 cm. Recall that $\alpha = C_{building}/C_{source}$, and it is a measure of both the indoor contaminant vapor concentration and contaminant vapor intrusion rate. The results are plotted in this way to facilitate comparison with numerical modeling results presented by Loureiro et al. (*9*). Figure 3 corresponds to the case where the contaminant vapor source lies adjacent to the building foundation ($L_T = 0$) and is roughly equivalent to the radon intrusion scenario modeled by these authors. The screening model predicts results that are in good qualitative and quantitative agreement with the detailed numerical modeling results [i.e., see Loureiro et al. (*9*), Figure 11]; both predict that α (and hence the intrusion rate) is independent of k_v for "small" values of k_v and becomes proportional to k_v at "large" values of k_v. The transition between these two regimes occurs near $k_v = 10^{-8}$ cm². For $k_v < 10^{-8}$ cm², the

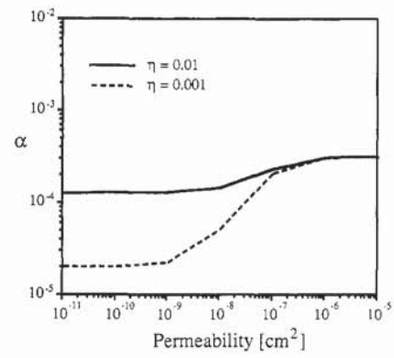

Figure 5. Dependence of attenuation coefficient, α, on soil permeability, k_v, as predicted by eq 21 for the parameters listed in Table II and $L_T = 1000$ cm.

soil gas flow rate through the cracks becomes so low that diffusion is the dominant transport mechanism and α is therefore independent of k_v. For $k_v > 10^{-8}$ cm², on the other hand, containment vapors are swept into the building primarily by convection. In this limit, $\alpha \rightarrow Q_{soil}/Q_{building}$ and becomes proportional to the resistance to flow (as measured by k_v). In this case the proposed screening model predicts $0.001 < \alpha < 0.01$ for $10^{-7} < k_v < 10^{-6}$ cm², which happens to fall in the range of values typically reported for radon intrusion studies. Figure 3 also indicates that the screening model predicts a dependence of intrusion rate and attenuation on the size of the crack, with the effect being more pronounced at lower permeabilities. As the crack size decreases, resistance to both diffusive transport and soil gas flow increases; thus, α is always predicted to be less for $\eta = 0.001$ than for $\eta = 0.01$. The decrease in flow rate predicted by eq 24 is apparently not as significant, however, as the increased resistance to diffusion through foundation cracks. Thus, for practical purposes, it can be concluded that the effect of crack size on contaminant vapor intrusion rates will be relatively insignificant in the limit of convective-dominated transport.

Figures 4 and 5 present model predictions for cases where the contaminant vapor source is located some distance L_T away from the foundation. In each figure the dependence of α on k_v is a sigmoidal-shaped curve, where α becomes independent of k_v in the limits of "large" and "small" soil permeabilities. In the limit of less permeable soils, soil gas flow rates are so low that vapor intrusion is governed entirely by the relative rates of diffusion through the soil and foundation. As the soil becomes more permeable, the "sweeping" of contaminant vapors into the building by soil gas flow increases the intrusion rate. At some point, however, diffusion from the containment vapor source to the region of soil gas flow limits the rate of contaminant vapor transport. For highly permeable soils, therefore, α becomes independent of k_v and only weakly dependent on foundation properties. The transition between Figures 4 and 5 also illustrates that α and the intrusion rate become less dependent on foundation properties as L_T increases. This is evidenced by the convergence of the "low" and "high" k_v asymptotes, and the $\eta = 0.001$ and $\eta = 0.01$ predictions as L_T increases; in the limit $L_T \rightarrow \infty$, diffusion through soil becomes the limiting transport mechanism.

Figures 3–5 illustrate the necessity of developing models that incorporate both convective and diffusive transport mechanisms. Single transport process based models cannot predict the wide range of behavior exhibited in these figures, nor can they explain the difference in the obser-

vations of Nazaroff (*1, 2*) for radon intrusion, and those of Hodgson et al. (*3*) for vapor transport of contaminant vapors from a landfill. The sample calculations also illustrate that the soil type can have a significant impact on the indoor vapor concentration, since Q_{soil} will be dependent on the soil permeability, and the effective porous media diffusion coefficient is sensitive to changes in soil porosity and moisture content. Being an analytical solution, eq 21 is easily used to study the sensitivity of model predictions over a range of reasonable soil and building characteristics. The major limitation to practical applications of the model is the lack of site-specific η values. It is not likely that such values can be easily measured; however, one can use the model to examine predictions for a realistic range of such values in order to determine the effect of this parameter at any given site. Clearly, predictions are insensitive to η in the limit of "permeable" soils and large source–foundation separations. A realistic range for η can be proposed by considering physical realizations corresponding to specific values of η. For example, η = 0.01 corresponds to a 1-cm-wide crack running the length of basement floor/walls every 100 cm.

It should be noted that Figures 2–5 contain model predictions for specific soil characteristics and building dimensions and are presented for illustrative purposes. The results should not be extrapolated to other sites not corresponding to the chosen parameters.

Extension of Theory to Relatively Permeable Foundation Walls

In the work of Garbesi and Sextro (*8*) it is assumed that vapor intrusion occurs through permeable below-grade walls, rather than through foundation cracks and openings. On the basis of this assumption, one can follow the approach used to derive eq 21 to obtain the following equivalent expression:

$$\alpha = \left[\left[\frac{D_T^{eff}A_B}{Q_{building}L_T}\right]\exp\left(\frac{Q_{soil}L_F}{D^F A_B}\right)\right]\Bigg/\left[\exp\left(\frac{Q_{soil}L_F}{D^F A_B}\right) + \left[\frac{D_T^{eff}A_B}{Q_{building}L_T}\right] + \left[\frac{D_T^{eff}A_B}{Q_{soil}L_T}\right]\left[\exp\left(\frac{Q_{soil}L_F}{D^F A_B}\right) - 1\right]\right] \quad (26)$$

which is similar to eq 21, except A_{crack} is replaced by A_B, D^{crack} is replaced by D^F, the effective diffusion coefficient through the porous foundation floor and walls, and L_{crack} is replaced by the foundation/wall thickness L_F. Equations 4–7 and 12 should be used to calculate D^F. While eqs 26 and 21 appear similar, they can predict quite different results. Equation 26 is independent of the area of cracks/openings because intrusion is assumed to occur uniformly over the floor/wall area. For a given Q_{soil}, therefore, the soil gas velocity through the floor/walls is lower for the permeable floor/wall case. The impact of this is that eq 26 may predict that transport through the foundation is diffusion dominated, while eq 21 predicts that it is convection dominated, for a given Q_{soil} and $D^{crack} = D^F$.

Extension of the Theory to Transient Problems

Equation 21 provides a screening estimate of indoor vapor concentrations, but does not account for depletion of the contaminant vapor source. This assumption is reasonable when short-term exposures are being estimated and does provide a conservative (upper bound) estimate for long-term exposures. There are situations, however, when more realistic long-term exposure estimates are desired and it is unlikely that the source will remain constant for a long period of time (usually ~70 years for most exposure estimates). Many processes can contribute to an unsteady source, including the depletion due to transport away from the source, biodegradation, and chemical reaction. Of the three processes, the depletion due to transport is most often modeled, due to the current uncertain quantification of the other two. A first-order estimate of whether or not significant changes will occur over a given time period τ is obtained by calculating the mass of contaminant emitted from the source over that time period (τE) and comparing it with the initial residual contaminant mass in the soil directly below the building ($\rho_b C_R \Delta H_c A_B$):

$$\tau E \overset{?}{=} \rho_b C_R \Delta H_c A_B \quad (27)$$

where C_R and ΔH_c denote the average residual contaminant level in the soil (g/g of soil) and the thickness of the vertical interval (cm) over which the contaminant is distributed, respectively, and E is given by eq 16. If the left-hand side of eq 27 is greater than the initial mass of contaminant right-hand side, then it is possible that the contaminant lying beneath (or adjacent to) the building will eventually volatilize and enter the building. The validity of this assumption will depend on site characteristics.

The simplest extension of the model is derived by invoking the quasi-steady-state assumption used by Thibodeaux and Hwang (*15*) for single-component contaminants or mixtures of compounds having similar vapor pressures and molecular weights. In this approach it is recognized that the source–building separation increases with time due to depletion; however, it is assumed that the rate at which a steady-state vapor concentration profile is established is much greater than the rate at which depletion occurs. At any time, therefore, the emission rate is given by eq 16 with L_T replaced by the source–building separation at that time. Implicit in this approach is the assumption that depletion occurs first from the layers of contaminant closest to the building floor and walls, and a hypothetical "depletion zone" grows with time. In a sense, the mass of contaminant incorporated in the soil "dries up", beginning at the edge closest to the building. This is a reasonable assumption for diffusion-dominated transport to the building–soil interface, but not valid for convection-dominated transport from contaminated soil adjacent to a building floor. With this limitation in mind, eq 16 combined with a mass balance provides a mathematical expression of the quasi-steady-state assumption:

$$\rho_b C_R A_B \frac{d\delta}{dt} = \left[\frac{D_T^{eff}A_B C_{source}}{(L_T^0 + \delta)}\right]\left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - \left[\frac{C_{building}}{C_{source}}\right]\right]\Bigg/\left[\left[\frac{D_T^{eff}A_B}{Q_{soil}(L_T^0 + \delta)}\right] \times \left[\exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}A_{crack}}\right) - 1\right] + \exp\left(\frac{Q_{soil}L_{crack}}{D^{crack}C_{crack}}\right)\right] \quad (28)$$

where δ, t, and L_T^0 denote the "depletion zone" thickness (δ = 0 at t = 0) (cm), time (s), and initial contaminant–building floor separation (cm), respectively. Equation 28 can be rearranged and rewritten in the form

$$d\delta^*/dt = \psi/(\beta + \delta^*) \quad (29)$$

where

$$\delta^* = \delta/L_T^0 \quad (30)$$

$$\psi = D_T^{eff} C_{source} / (L_T^0)^2 \rho_b C_R \quad (31)$$

$$\beta = \left(\frac{D_T^{eff} A_B}{L_T^0 Q_{soil}}\right)\left[1 - \exp\left(-\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right] + 1 \quad (32)$$

In this analysis it is assumed that the residual contaminant level in soil C_R is uniform, D^{eff} is constant as δ increases, and the ratio $C_{building}/C_{source} \ll 1$. Equation 29 can be solved to obtain

$$\delta^* = -\beta + \sqrt{\beta^2 + 2\psi t} \quad (33)$$

The time τ_D required to deplete a contaminated zone of thickness ΔH_c can be obtained from eq 33, by setting $\delta^* = \Delta H_c / L_T^0$

$$\tau_D = \frac{[\Delta H_c / L_T^0 + \beta]^2 - \beta^2}{2\psi} \quad (34)$$

Equation 34 predicts that τ_D increases with increasing L_T^0 and C_R; increasing L_T^0 decreases the initial diffusive driving force, while increasing C_R increases the contaminant capacity of the contaminated soil zone. If $\tau \geq \tau_D$, the average emission rate into the basement $\langle E \rangle$ over the time period τ_D is obtained by a simple mass balance:

$$\langle E \rangle = \rho_b C_R \Delta H_c A_B / \tau \quad (35)$$

For time periods $\leq \tau_D$, the average emission rate is given by

$$\langle E \rangle = \frac{\rho_b C_R \Delta H_c A_B}{\tau}\left(\frac{L_T^0}{\Delta H_c}\right)[(\beta^2 + 2\psi\tau)^{1/2} - \beta] \quad (36)$$

which can be derived by substituting eq 33 for δ^* (δ/L_T^0) into the right-hand side of eq 28 and then averaging the resulting expression over the time period τ. As expected, eq 36 predicts a decrease in $\langle E \rangle$ with increasing τ. The corresponding long-term average attenuation coefficient $\langle \alpha \rangle$ is then

$$\langle \alpha \rangle = \frac{\rho_b C_R \Delta H_c A_B}{Q_{building} C_{source} \tau}\left(\frac{L_T^0}{\Delta H_c}\right)[(\beta^2 + 2\psi\tau)^{1/2} - \beta] \quad (37)$$

While eqs 28–37 form a more sophisticated model than eq 21, one must be aware that increasing the level of sophistication usually increases the amount of site-specific information required. More sophisticated screening models are usually also based on additional assumptions, and one must be careful to ensure that these assumptions are valid for specific site characteristics.

Vapor Equilibrium Models

The models presented above require an estimate of the source vapor concentration, C_{source}. Two main approaches are used in vapor transport modeling; in the first C_{source} is assumed to be proportional to the residual level in the soil, and in the second C_{source} is independent of the residual level, but is a function of composition. The former is applicable in the limit of "low" residual levels where compounds are sorbed to the soil, dissolved in the soil moisture, and present in the vapor space; the latter is applicable for "high" residual levels where free-phase liquid or precipitate is trapped in the soil interstices. A more detailed description of this topic can be found in Johnson et al. (*12*), and it is not appropriate to repeat the discussion here. It is important to note, however, that if one chooses an incorrect model for predicting C_{source}, then it is possible to over- or underpredict the actual C_{source} value by orders of magnitude.

Conclusions

We have derived and illustrated the use of a heuristic model of the intrusion rate of subsurface contaminant vapors into buildings through basement, or foundation, floors and walls. The model provides an exposure assessment screening-level tool; it can be used to identify sites, or contaminant levels, where contaminant exposures through a vapor inhalation pathway may cause adverse health effects. It can also be used to help identify sites where more detailed numerical simulation, or field sampling, is appropriate. The model was used to make predictions of basement vapor concentrations over a range of realistic parameters. It is clear from the wide range of results that field data will only be correlated by models such as this that incorporate both convective and diffusive transport mechanisms.

Currently, there are few reported experimental studies that are sufficiently detailed to compare with model predictions. However, the range of behavior, dependence on relevant parameters, and limiting bounds of the model are in qualitative agreement with published case histories. At this point, more detailed field studies and numerical simulations are needed to help validate this screening-level model.

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