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A Review of Vapor Intrusion Models

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Abstract

A complete vapor intrusion (VI) model, describing vapor entry of volatile organic chemicals (VOCs) into buildings located on contaminated sites, generally consists of two main parts—one describing vapor transport in the soil and the other its entry into the building. Modeling the soil vapor transport part involves either analytically or numerically solving the equations of vapor advection and diffusion in the subsurface. Contaminant biodegradation must often also be included in this simulation, and can increase the difficulty of obtaining a solution, especially when explicitly considering coupled oxygen transport and consumption. The models of contaminant building entry pathway are often coupled to calculations of indoor air contaminant concentration, and both are influenced by building construction and operational features. The description of entry pathway involves consideration of building foundation characteristics, while calculation of indoor air contaminant levels requires characterization of building enclosed space and air exchange within this. This review summarizes existing VI models, and discusses the limits of current screening tools commonly used in this field.

Introduction

Other reviews of vapor intrusion (VI) models for volatile organic chemicals (VOCs) have been published in recent years (1–3). This present review seeks to provide a comprehensive overview of vapor intrusion models that deal with non-radon vapor intrusion, highlighting particularly the differences between one, two and three-dimensional models, and extending coverage to modeling results more recent than those covered in the above cited reviews.

VI models all involve simulation of the transport of contaminant vapor through soil and its entry into a building. The focus of such models is generally prediction of the contaminant concentration attenuation (i.e. concentration reductions) relative to a subsurface source concentration, during the transport process and entry into a building. The soil transport portion of VI models was partially built upon the previous work performed on pesticide movement in soil (4–7), while the entry process modeling was greatly influenced by earlier studies of radon vapor intrusion (8–11). Though the subject has changed in terms of the contaminants of concern, the governing equations and general scenario are still often quite similar to those considered earlier.

Pesticide transport simulation models can be traced back to late 1960s (12–13), e.g. DDT (14). These models were concerned with pesticide fate and transport including leaching, volatilization and biodegradation. Factors such as surface runoff, evapotranspiration, absorption, and drainage were also considered. Of course, not all these elements are relevant for VI models.

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Radon intrusion simulations were developed starting in the 1970s (8, 10–11, 15–16). The general pathway of radon intrusion into buildings is through building foundation cracks and permeable walls, often driven by indoor depressurization, which is similar to the VI pathway involving VOCs. One difference is that the radon source is generally considered homogeneously distributed in the soil, which can make the diffusion due to concentration gradients relatively less important than in the VI case, where there is a well-defined subsurface source. The main focus of many radon models was to obtain accurate estimates for soil gas flow rate through building foundation entry cracks. Still, describing radon transport in soil can be relevant to some cases, especially those involving low subslab permeability and soil heterogeneities. Significant radon soil vapor concentration gradients can be induced by strong soil gas flow due to indoor depressurization (17–19).

For a typical vapor intrusion scenario including a groundwater source and building of concern surrounded by open ground, there is a significant soil vapor concentration gradient from the source to the sink/receptor, regardless of whether the latter is open ground or a foundation slab crack. Again, the location and distribution of the contaminant source is a difference between the radon models and the VI models of interest here. Also, biodegradation pathways are irrelevant in radon modeling. In this review, only VI models of VOCs are considered. Readers are directed to Nazaroff (1992), Gadgil (1992), Robinson and Sextro (1997) and Andersen (2001) for further information about radon intrusion (models) (23–26).

It is now generally agreed that the diffusion of contaminant in soil typically determines its soil vapor concentration profile in the absence of biodegradation (3, 20). This conclusion has been supported by the results of comprehensive three-dimensional (3-D) numerical models, describing most typical scenarios (21–22). Advection processes influence concentrations only locally in the immediate vicinity of the building of interest. Earlier radon modeling work has been adopted in VI models to describe the local advection processes that influence entry rates into a building (9–11). One well-known example is in the application of the Nazaroff equation (27) for calculation of soil gas entry rate. This approach was used in the Johnson-Ettinger (J-E) model (28), the introduction of which was a landmark in the study of VI.

Polluted groundwater is typically assumed as the VI contaminant source in most VI models. Despite this, contamination by free non-aqueous phase liquid (NAPL) in unsaturated media could also serve as a VI source in some instances. In the former case, the most common way to characterize the source is by measurement of the contaminant concentration in groundwater, followed by calculation of source vapor concentration above the water phase, using an appropriate Henry's law constant (29–30). In the case of a free NAPL phase, calculation of vapor pressure might be possible, though direct assessment of soil gas data has been recommended (29). Since the focus of most of current VI models is prediction of contaminant vapor concentration attenuation factors relative to a specified soil gas concentration at some depth (31), it really does not make a difference which type of source is present, so long as a source contaminant vapor concentration is established at a known depth.

A complete VI model should describe the whole process from source to receptor, including soil vapor transport and entry into the building. In some cases, simplified scenarios have been offered considering only the former process. This is because most key environmental factors, such as advection, diffusion, biodegradation, adsorption and so on, mainly play a role in that step. The problem for all models, simplified or comprehensive, is that it is difficult to know and to take into the influence of all relevant environmental factors. Obviously for good VI model predictions, it is critical to capture the key environmental

factors describing the scenario of interest, and these will vary from site to site. Thus it is essential to know in what scenario a user wants to apply a particular model, and carefully consider which parameters might be critical in that case. In order to help in understanding the key factors and assumptions used in modeling work in this field, the currently used VI models are reviewed. Following this model review is a discussion of VI screening tools, accompanied by some suggestions regarding their limitations.

Models simulating contaminant vapor transport in soils

The separation of vapor source from receptor, e.g. a contaminated groundwater plume from a building of interest, makes the quantitative description of contaminant transport through soil necessary. For a typical vapor intrusion scenario, which includes a groundwater source and a building of concern surrounded by open ground, the contaminant concentration profile is mainly determined by diffusion, as already noted above. In some cases it can also be influenced by advection, biodegradation and absorption processes, as discussed below.

Even though advection is often a minor process in terms of contaminant transport through the soil, it must often be accounted for locally (i.e., near areas of significant pressure gradient such as building entry points). Typically, it is assumed that the soil gas flow follows Darcy's Law, and thus its magnitude and direction are determined by the pressure gradients in the soil. If these pressure gradients are not large compared to atmospheric pressure, air (the main component of soil gas) can be safely assumed incompressible. This is almost invariably an appropriate assumption in vapor intrusion scenarios.

The general, transient form of Darcy's law for soil gas flow is

$$\frac{\partial p}{\partial t} - \frac{p_{atm} k_g}{\phi_g \mu_g} \nabla \cdot (\nabla p) = 0 \quad (1)$$

$$q_g = \frac{k_g}{\mu_g} \nabla p \quad (2)$$

Where p is the soil gas pressure [M/L/T²], t is time [T], p_{atm} is atmospheric pressure [M/L/T²], k_g is the soil permeability to gas flow [L²], ϕ_g is the air filled porosity [L³_{gas}/L³_{soil}], μ_g is the soil gas viscosity [M/L/T] and q_g is the soil gas flow per unit area [L³_{gas}/L²_{soil}/T]. This equation neglects density-driven flow effects and gravity, which are expected to be insignificant for the problems of interest here.

The contaminant vapor transport in the soil is then generally described by an advection-diffusion equation (21):

$$\phi_{g,w,s} \frac{\partial c_{ig}}{\partial t} = - \nabla \cdot (q_g c_{ig}) - \nabla \cdot \left(\frac{c_{ig}}{H_i} q_w \right) + \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (3)$$

$$\text{Where } \phi_{g,w,s} = \phi_g + \frac{\phi_w}{H_i} + \frac{k_{oc,i} f_{oc} \rho_b}{H_i} \quad (4)$$

In equation (3) $\phi_{g,w,s} \frac{\partial c_{ig}}{\partial t}$ represents the time dependence of contaminant mass contained in the soil gas, soil moisture and soil organic carbon as represented in equation (4);

$-\nabla \cdot (q_g c_{ig}) - \nabla \cdot \left(\frac{c_{ig}}{H_i} q_w \right)$ is the advection term reflecting contaminant movement with soil gas and, if relevant, groundwater flow; $\nabla \cdot (D_i \nabla c_{ig})$ describes the diffusion of contaminant in the soil gas phase (contaminant diffusion through the water phase is neglected due to much lower diffusivity in a condensed phase as compared to a vapor phase); ϕ_w is the moisture filled porosity [$L^3_{\text{water}}/L^3_{\text{soil}}$]; H_i is the contaminant Henry's Law constant [$(M_i/L^3_{\text{gas}})/(M_i/L^3_{\text{water}})$], linearly relating vapor phase contaminant concentration to water phase concentration; $k_{oc,i}$ is the sorption coefficient of contaminant i to organic carbon in the soil [$(M_i/M_{oc})/(M_i/L^3_{\text{water}})$]; f_{oc} is the mass fraction of organic carbon in the soil [M_{oc}/M_{soil}]; p_b is the soil bulk density [$M_{\text{soil}}/L^3_{\text{soil}}$]; c_{ig} is the concentration of contaminant i in the gas phase [M_i/L^3_{gas}]; q_w is the water flux in the vadose zone if relevant [$L^3_{\text{water}}/L^2/T$]; D_i is overall effective diffusion coefficient for transport of contaminant i in porous media [L^2/T]; R_i is the contaminant i loss rate by biodegradation [$M_i/L^3_{\text{soil}}/T$] and $\phi_{g,w,s}$ is the effective transport porosity [$L^3_{\text{air}}/L^3_{\text{soil}}$], defined in equation (4). Equation (3) can also be applied to describe oxygen transport in the soil, as this may be relevant to the modeling of biodegradation under aerobic conditions.

The value of q_g obtained from equation (2) above is needed for solving equation (3). Because in most VI scenarios, contaminant concentrations are very low, solution of equation (2) may be decoupled from solution of equation (3), without introducing any significant error.

D_i in equation (3) is typically obtained from the Millington and Quirk equation (32):

$$D_i = D_i^g \frac{\phi_g^{10/3}}{\phi_t^2} + D_i^w \frac{\phi_w^{10/3}}{\phi_t^2} \quad (5)$$

Where D_i^g is the contaminant diffusivity in air [L^2/T], ϕ_t is the total soil porosity [$L^3_{\text{pores}}/L^3_{\text{soil}}$] and D_i^w is the contaminant diffusivity in water [L^2/T]. In certain instances, a third term, describing mechanical dispersion of contaminant due to movement of groundwater has been added (33). In application, equation (3) can be simplified for certain cases allowing convenient analytical solution, as shown in Tables 1 and 2, for non-biodegradation and biodegradation cases, respectively.

VI models can be divided into two groups. One class includes simple screening tools used in site evaluation, and most of these are 1-D analytical models. The others are the multi-dimensional numerical models used to examine in more detail the influence of environmental factors in the contaminant vapor concentration attenuation processes. In the former class of models, as a result of the simplification of the scenarios, application is straightforward, though the accuracy of predictions may be questionable (see below). On the other hand, the latter numerical models, capable of simulating complicated environmental processes, require significant computational effort, which has limited their use. This difference is not absolute, and screening tools can still reach a good standard of accuracy if most important environmental factors are included for specified scenarios, and numerical simulations are now much more accessible outside the research community, due to the availability of user-friendly equation solver packages for desktop computers.

Transport models without biodegradation

The majority of present VI models have been developed only for steady state analyses. Most are one-dimensional and involve analytical solutions. Table 1 summarizes most published models that do not explicitly account for biodegradation, along with their key governing equations. While the “del” notation is used throughout the table, it should be understood that

in the case of 1-D models, this simply represents “ d/dz ”, or an ordinary, one-dimensional derivative in the vertical direction. In the 2-D models, its use indicates partial derivatives in vertical and horizontal directions, and of course in 3-D models, its use indicates the usual vectorial operator expressing partials in all three coordinate directions.

One-dimensional (1-D) models

Again, the prevailing view is that diffusion is the main mechanism determining non-biodegradable contaminant soil vapor transport for cases with moderate soil permeabilities (21–22, 28, 40). The advection induced by indoor air pressure difference from ambient only affects a small area immediately around the building of interest. This is why many 1-D models do not even include an explicit advective term. It also bears noting that in a 1-D steady state diffusion model, in uniform soil, the concentration profile is always independent of diffusivity, though the rate of diffusion will be proportional to diffusivity. Hence, it needs to be remembered that looking only at the concentration profile in any steady state diffusion case (1-D or multidimensional) will not by itself indicate the rate of contaminant transport until information on diffusivity is also considered.

The 1991 Orange County Health Care Agency (OCHCA) vapor intrusion model (35) and contaminant emission rate calculation in Wrighter and Howell’s 2004 study (39) employed the mathematically simplifying assumption of unidimensionality in order to describe steady state contaminant transport from a plane source at a particular vertical distance from the building of interest. In the OCHCA model (35), a contaminant transport rate into the building is estimated assuming diffusion from the source to a subslab (i.e. immediately beneath the building) at zero concentration, and then applying an empirical attenuation factor for the slab.

Another popular screening tool, the J-E model (28) also involves solving a 1-D diffusion model, except that it does not assume the subslab contaminant soil vapor concentration to be negligible, as did the above model. Another minor difference is that in the OCHCA approach, the actual building foundation footprint size is assumed as the effective source area, while in the J-E model a total “contact area” of building foundation with soil is used. This is actually problematic for the J-E model, as discussed below. The J-E model has also been included in a commercial software package, BP’s Risk-Integrated Software for Cleanups (RISC) (52), offered by groundwatersoftware.com. In Park’s study (36), the J-E model was slightly modified to include equilibrium partitioning for total petroleum hydrocarbons.

Little et al. in 1992 (34) constructed two scenarios to represent the subsurface transport of VOCs from as a planar source located at some depth below a structure (#1 model) and uniform source beneath, and surrounding, a structure’s foundation (#2 model). The solutions were obtained for transient conditions. The #1 model in Little et al. was then modified in Symms et al. (41) to include a concrete building foundation by using a crack factor.

In the 1994 CSOIL model (37), only diffusion was considered as governing soil vapor transport, but in a series of models based on that model, such as VOLASOIL (43–44) and CSOIL 2000 (45), a uniform advection induced by depressurization of a crawl space or enclosed space was combined with diffusion. The contaminant vapor concentration in the crawl space and indoor space was assumed insignificant compared to that of the source, and a steady state contaminant mass flow rate was obtained analytically. Those models are actually all simplified forms of Jury’s even earlier model (4–7) but without biodegradation. CSOIL is also the basis of the RISC-Humaan vapor intrusion model component. Murphy and Chan (42) more recently also included both uniform advection and diffusive fluxes, and simulated mass exchange between multi-media environmental compartments by using

different mass transfer coefficients. In some limiting cases, this mass transfer model can be reduced to a three-compartment system, analogous to the J-E model (28).

Advection could in certain cases also be the principal driving force for lateral, rather than vertical, contaminant transport (such as where a landfill is the source of the vapor of concern). In the distant landfill scenario (#3 model of Little et al. (34)), a large pressure difference between a landfill site and ambient was taken as the driving force for transport from the landfill site to a building of interest. The majority of VI models considered in this review focus mainly on vertical transportation in the absence of large horizontal pressure gradients.

Two-dimensional (2-D) models

Generally, 2-D models can address the problems associated with representing heterogeneous (multiple) boundaries in a scenario of interest, by accounting for both horizontal and lateral transport. As the difficulties in obtaining analytical solutions increase greatly when the dimensionality of a model increases, a common approach is to simplify transport mechanisms and use approximate boundary conditions to simplify solution. For example, if it is reasonable to assume diffusion as the main contaminant vapor transport mechanism in soil (as already noted above), then the governing equation for contaminant transport in soil becomes the Laplace equation, thereby avoiding introduction of the advective terms that make solution much more complicated. This approximation has been useful in two studies that led to some general conclusions regarding the nature of the VI problem.

Yao et al. (22) used a Schwarz-Christoffel transform (53) to study the contaminant concentration near a subslab perimeter crack, assuming an infinite uniform groundwater contaminant source beneath a building of interest. Advection was not considered in this estimate, and only when an estimate of soil gas flow through the crack was needed for obtaining indoor air concentrations in a separate second step of calculation was it explicitly included. What this showed was that the contaminant concentration profile around a building can first be estimated separately from a simple analytical expression, and then the contaminant entry rate based on this profile can be estimated in a second step of calculation, knowing the rate of soil gas advection through a foundation breach into the building. Full numerical 3-D simulations confirmed that the existence of a foundation crack does not play an important role in determining the contaminant subslab concentration profile in the soil, for a reasonable indoor depressurization. The analytical solution so obtained for the contaminant profile suggested that it is mainly the characteristic length ratio of source depth to building foundation depth that determines the subslab concentrations.

Lowell and Eklund (40) defined a 2-D scenario to study the influence of lateral separation between contaminant source and building. The results showed that soil contaminant vapor concentration decays exponentially with the lateral distance from source and that vertical source depth does not matter much compared with lateral separation from the building of concern. One unresolved issue in that study was that of the role of building foundation, although Lowell and Eklund noted that the variation of subsurface concentration with depth corresponding to foundation depths was less than an order of magnitude in most cases. The influence of lateral separation from source was recently further explored (38). The Yao et al. (22) analytical approximation was extended to consider the influence of lateral separation on subslab concentration near a perimeter crack, and gave a result similar to Lowell and Eklund (40), even after the effect of the building foundation was included. It needs to be recognized, however, the route of lateral diffusion could involve a path of non-uniform geology; for example, the ground surface might include both paved and unpaved (i.e., open to the air) sections. The effect of this can be significant, as the typical cited exponential concentration

decay with horizontal distance from a ground surface depends upon having a surface open to atmosphere.

Three-dimensional (3-D) models

It is usually impossible to obtain analytic solution to all but the simplest transport problems in 3-D coordinates, except for the “pseudo 3-D”, axisymmetric cases. However, if the extra effort in using a 3-D model is to be justified, the 3-D model must be capable of doing what models of lower dimension cannot do. 3-D models can deal with complicated processes such as coupled oxygen and contaminant transport and complicated boundary conditions.

Abreu and Johnson (21) developed a three-dimensional numerical model (the ASU model) of the soil vapor-to-indoor air pathway. The finite difference codes of the numerical model were written by Abreu (50). The model was used to simulate various scenarios, involving an infinite homogenous source, over the whole model domain. The building foundation above that source was assumed to have a perimeter crack in its foundation, and there was open surface around the building. These reported simulation results were later been compared to the approximate analytical solution (22) described above, and this again confirmed that diffusion mainly determines subsurface contaminant profiles.

In Bozkurt et al. (47) and Pennell et al. (48), a commercially available CFD package, Comsol Multi-physics, was used to construct a similar 3-D numerical model (the Brown model) which was solved with a finite element method (as distinct from Abreu and Johnson’s finite difference solver (21)) and of course gave similar results for comparable scenarios. Using the Brown model, many different scenarios were considered including a single building on an open field, a paved parking lot around building, a nearby detached garage, porous sub-base beneath the foundation multi-layered soils, and a scenario of adjacent buildings as might characterize an urban setting (48, 54). These scenarios are too complicated to be described with a 1-D model or a 2-D model. Most of the model parameters in these later studies were the same as used by Abreu and Johnson (21), except for a small difference in the crack boundary conditions. In the later models (47–49), a pressure boundary condition was assumed while in Abreu and Johnson (21) an analytical approximation governing the flux through a tube was applied. The results show the soil pressure gradient fields produced by both approaches are virtually identical. Pennell et al. (48) have also argued that because building air exchange rates are usually variable and unmeasured, predictions of the indoor air concentration attenuation factor might not be a good indicator of the vapor intrusion effect. Instead the contaminant mass flow rate into the building is suggested as an alternative measure of risk, as it is purely determined by the transport model itself, independent of building operational parameters, except indoor pressure.

Transport models involving biodegradation

Biodegradation can play a significant role in soil contaminant concentration attenuation (55–63), and some simulation studies have included biodegradation effects.

Table 2 presents the main working equations of various VI models that incorporate biodegradation, though the actual form of the biodegradation rate expression is shown here only generically as “ R_i ”. Table 3 shows the different forms of R_i that have been assumed by different workers and Table 4 shows some of the corresponding rate constants. Models labeled “1 species” consider only contaminant loss kinetics, whereas those labeled “2 species” explicitly include oxygen consumption as part of the biodegradation process, since oxygen can also be a limiting substrate.

1-D models involving biodegradation

Analytical solutions to 1-D vapor intrusion scenarios including biodegradation are possible. The #3 model of Little et al. (34) was used by Sanders and Stern (69), where an empirical first-order decay factor represented degradation of contaminant. Ririe and Sweeney (63) described the normalized hydrocarbon concentration profile in unsaturated soil subject to aerobic conditions in the whole domain in which first order biodegradation occurs. Using the same assumption, Johnson et al. (20) also incorporated a first order degradation term into a modification of the J-E model in a three-layer scenario. In Mills et al. (68), Johnson's model (20) was modified by adding a nonzero background (the Vapor Intrusion Model, VIM). The R-UNSAT model (64) also used the same governing equation but with different upper boundary conditions to simulate cases of maximum and minimum contaminant mass flow rate escaping from the soil surface. Jeng et al. (67) included biodegradation in a model in which, diffusion, instead of advection, became the major mechanism of contaminant lateral transport.

In pesticide leaching models, both uniform advection induced by rainfall and natural biodegradation are important. The pesticide model developed in series of papers by Jury (4–7) was modified for application in vapor intrusion, such as by Vlier-Humaan, while another two pesticide models (70, 90) were also applied in RISC. Anderssen et al. (75), made a modification of these models to remove two shortcomings related to limited initial conditions and homogenous surface boundary conditions. The analytical solutions were given without detailed explanation. For the #2 model of Sanders and Stern (69), the surface area of a zone of influence was substituted for the soil surface area used in Jury's model (4–7). The contaminant source was assumed to be contained in a particular depth range from the soil surface. Jury's model was also adapted in the Turczynowicz and Robinson (T&R model) (76), and the difference from Sanders and Stern's model (69) is that the contaminant source zone was presumed be in contact with the soil surface, which is also the bottom of a crawl space. Instead of assuming the crawl space concentration negligible, its concentration was taken into consideration in the T&R model (76). All of these three models assumed a first order biodegradation as assumed in Jury's model (4–7). Lin and Hildemann (77) developed a transient analytical model to predict VOC gaseous emissions from landfills using the same governing equation and boundary conditions as used in Jury's model. In their study, the scenario of an instantaneous release layer of contaminant liquid solvent from a subsurface plane source was simulated using a Dirac delta function as an initial condition.

For some contaminants, for example, petroleum hydrocarbons, only aerobic conditions are favorable for significant biodegradation (91–92), which makes consideration of multispecies transport and reaction appropriate; i.e. oxygen transport from the surface also needs to be explicitly included. The most common assumption is that oxygen is abundant in the surface soil, and that it is consumed by biodegradation as it diffuses towards the contaminant source. The transport processes of the contaminant and oxygen are independent of each other, except through the reaction rate term.

Ostendorf and Kampbell (60) introduced the transport of oxygen into a 1-D contaminant steady state diffusion model which includes biodegradation, but the simulation of oxygen transport has no real significance since the oxygen concentration profile does not influence the contaminant concentration profile. In oxygen limited cases, the transport of oxygen also needs to be coupled with the transport of contaminant vapor in the soil.

The concept of an aerobic/anoxic interface used by Roggemans et al. (78) was based on the assumption that most reaction occurs at the interface to which both contaminant and oxygen diffuse in stoichiometric proportions. The equations of hydrocarbon vapor and oxygen transport were solved to give the depth of the interface. This approximation is almost true if

the biodegradation rate is fast, compared to diffusion rates, as was earlier discussed by Borden and Bedient (93).

Davis et al. (66) also employed the concept of a reactive interface to describe the oxygen concentration profile. The assumed zero order and first order reaction with respect to contaminant concentration were tested against the concentration profile of oxygen in soil. In Parker's model (80), the averaged zero order contaminant reaction rates were determined in different cases. Net contaminant mass flow rate into an enclosed space was obtained by subtracting the total reaction rate from the predictions of the J-E model. Based on the concept of an aerobic/anoxic interface, Devaull (79) further modified the J-E model to include biodegradation in the upper aerobic zone. Analytical solution for steady state was obtained by assuming mass continuity at the interface, and indoor air concentration is assumed to be the same as the subslab concentration, without the existence of a foundation slab in this model.

Verginelli and Baciocchi (81) included both anaerobic and oxygen limited aerobic biodegradation in a 1-D model, and the generation of methane was assumed during the anaerobic process.

2-D models involving biodegradation

There is a great variability of numerical biodegradation models of VI. R-UNSAT (65) provides numerical solution for 2-D multi-species transport models with radially symmetric boundaries. The advection simulation capability is limited to a constant aqueous transport of the contaminant, and this model cannot simulate building construction characteristics such as building foundations. The IMPACT model was originally developed by Talimcioglu et al. in 1991 (83–85) to provide soil cleanup criteria for hazardous waste sites, while in Sanders and Talimcioglu's study (94) the model was applied to estimate the volatilization of VOCs. This model describes a similar process as Jury's model but it also includes hydrodynamic dispersion. The effects of seasonal and short-term temperature and rainfall fluctuations were also examined. Hers et al. (82) used VADBIO to simulate vapor phase multispecies transport in soil and the effect of a building floor slab on transport processes. Biodegradation processes were also incorporated in this model in different forms, and the transport of oxygen and contaminant were coupled. Yu et al. (89) used a multi-phase compositional model CompFlow Bio, to study contaminant transport from groundwater to indoor air with scenario geometry predefined by a particular site. The transport of dense non-aqueous phase liquid (DNAPL) contaminant, released from a DNAPL source zone, into the groundwater was also simulated.

3-D models including biodegradation

In the further application of Abreu and Johnson's model (21), coupled first order biodegradation and oxygen transport were studied by Abreu and Johnson (87). That model assumes that first order biodegradation only occurs in the aerobic zone where the oxygen concentration is higher than 5% of the atmospheric concentration. The results of this 3-D model are consistent with Roggemans et al.'s hypothesis (78) regarding the depth of aerobic/anoxic interface, when the location of the interface is far from the building. Compared to the piecewise first order biodegradation approach used in Abreu and Johnson's model, in which the reaction rate is a function of contaminant concentration in the aerobic zone, Yao (86) considered a second order biodegradation involving both oxygen and contaminant concentration which was simulated incorporating biodegradation kinetics and oxygen transport into earlier developed model structures (22, 46–49, 51).

Models simulating contaminant vapor entry into buildings

The simulation of contaminant transport in the soil is the most difficult part of any simulation, but it is not all of it. There still needs to be a model for the vapor intrusion route from soil into building and, perhaps further, contaminant mixing into the indoor air.

Again, some studies (48–49) have suggested that calculating contaminant mass flow rate into the enclosed building space is a better alternative to calculating actual contaminant indoor concentration, due to the usual uncertainty in characterizing air exchange rates.

Equation governing escape of contaminant from the soil

We first consider the way that the contaminant vapor escapes from the soil, (or enters a building) which is the key to establishing the upper boundary condition of the soil transport equations. Similar methods are employed in both VI and radon intrusion research. In a review of numerical radon intrusion models by Andersen (26), three different ways of handling the soil surface/building entry boundary of radon vapor transport in soil were summarized; fixed concentration, diffusive soil-air layer (4–7) and indoor air concentration dependent flux (8, 95).

The general form of the boundary condition for soil surface or building entry can be expressed as:

$$Ac_{ig} + B\nabla c_{ig}|_{z=0} = f(x, y, 0) \quad (27)$$

Where A and B are constants used to characterize the boundary condition, (x, y, z) are the positional coordinates in the model domain, where z is the vertical direction and $z = 0$ is the soil surface. f is some boundary value function of (x, y, z) ,

The simplest assumption is that all ground surface is open including beneath the building, so that indoor air is exposed directly to the soil. This means treating the building footprint the same as ground surface open to atmosphere, where zero concentration is applied as a boundary condition. The value of flux of contaminant to the atmosphere is then the same as the flux into the house. In this case, equation (27) becomes

$$c_{ig}|_{z=0} = 0 \quad (28)$$

The contaminant mass flow rate into any upper space, including the building, is just equal to the general rate of contaminant escape from soil:

$$J_{us} = J_{soil} \quad (29)$$

Where J_{us} and J_{soil} are the contaminant mass flow rate into the upper space and out of soil, respectively (M/T).

Some studies have introduced diffusive layer theory as developed in Jury's model (4–7) to calculate the contaminant mass flow rate directly into an enclosed space. The diffusive layer is a thin virtual layer between the soil surface and atmosphere, and in this way a flux boundary condition can be applied to describe contaminant transport. The contaminant mass flux rate out of the soil surface equals the flux across the thin layer. In this case equation (27) becomes

$$\nabla c_{ig}|_{z=0} = f(x, y, 0) \quad (30)$$

However, this boundary condition is somewhat unrealistic for simulating any common buildings with floors or slabs that to some significant extent block soil gas entry. Thus this method was modified by explaining that the contaminant soil gas from the subsurface soil is actually entering a crawl space, which shares the same features with open surface, but with a concrete slab blocking flow.

Not all of the buildings have a crawl space without slab, and for buildings with basement or of slab-on-grade construction, the blocking effect of concrete slab is impossible to ignore. For houses with a concrete floor in contact with soil, the OCHCA vapor intrusion model (34) introduced an attenuation factor for flux attributable to the foundation of the building, but equation (28) was still used for the subslab boundary by assuming the subslab contaminant concentration is negligible compared to the source concentration. In this case, the contaminant mass flux into the upper space was governed by:

$$J_{us}=bJ_{soil} \quad (31)$$

where b is an empirical attenuation factor of flux attributed to the foundation slab of the building. It is, however, known from both field measurements and detailed simulation that subslab concentrations are not zero in true VI scenarios.

Another way to estimate the concrete slab blockage effect is to use the same approach as in the previously described diffusive layer theory by assuming the slab is permeable but with small permeability. In some sense this is a reasonable approximation to a slab with cracks, but it is difficult to define the relevant permeability of the concrete. In Ferguson et al.'s study (98), the slab was assumed as a combination of different materials in series.

The most popular, and arguably, realistic way to model structure entry is to introduce as a boundary condition some crack or breach hypothesis. Foundation cracks were identified in radon intrusion studies as the major entry route (8–11, 97). The development of Nazaroff's equation (27) to estimate volumetric flow rate into a crack was an important advance.

Nazaroff equation (27) is:

$$Q_{ck_JE} = \frac{2\pi k \Delta p L_{ck}}{\mu_g \ln(2d_f/w_{ck})} \quad (32)$$

Where Q_{ck_JE} is the soil gas volumetric entry flow rate [L^3/T], k is the soil permeability [L^2], Δp is the indoor air pressure difference of indoor air [$M/L/T^2$], L_{ck} is the length of the perimeter crack, μ_g is the viscosity of soil gas [$M/L/T$], d_f is the depth of the foundation [L], w_{ck} is the width of the crack [L].

This entry advection rate is not very important when considering contaminant transport in the soil as a whole, but it can be very important locally near the crack in determining contaminant entry rates. Contaminant mass flow rate into the enclosed building space can be calculated with a 1-D tube model such as in CSOIL2000 (45) and VOLASOIL (43–44) or 2-D plate flow model as used in Bozkurt et al. (48). The J-E model (28) and other models (20, 68, 79) based on it also employ combined advective and diffusive entry. Such entry models also provided a suitable boundary condition for multi-dimensional computational simulations, such as Abreu and Johnson (21, 87), Bozkurt et al. (47), Pennell et al. (48) and Yu et al. (89).

In the above multi-dimensional advection-diffusion boundary cases, equation (27) becomes

$$\nabla c_{ig}|_{z=0} = \begin{cases} 0 & \text{beneath the slab area} \\ f(x, y, 0) & \text{at the crack area} \end{cases} \quad (33)$$

where the zero reflects the impermeability of the slab and $f(x, y, 0)$ reflects an advective/diffusive profiles at a crack or breach.

This boundary condition obviously cannot be used in a 1-D model.

Johnson (31) has suggested that use of a ratio of soil gas entry flow rate to the indoor space volumetric flow rate of fresh air is a good alternative for avoiding use of Nazaroff's equation (27) in the original J-E model (28). The problem is that this value still remains tied to some understanding of indoor air exchange. Table 5 summarizes the different soil gas entry rates assumed in various VI models.

Indoor air concentration calculation

The basic idea in calculating indoor air concentration is considering the enclosed space of the building as a Continuous Stirred Tank (CST), or several CSTs in series, in order to simulate the building construction characteristics. The contaminant mass flow rate into the enclosed space must equal the out flow in steady state. This may be true even though the contaminant transport in the soil may be simulated as a transient process, because the time constant characterizing the indoor space is short compared with the time constants for soil transport.

The most basic model assumes only one CST, which consists of the whole dwelling space itself. This means the contaminant mass flow rate from the soil transport is distributed evenly throughout the entire structure. Another assumption is two CSTs in series, one is the dwelling space and the other is the crawl (or basement) space between the dwelling space and soil surface. Therefore, crawl space or basement air exchange rate and entry rate into the dwelling space are needed to calculate the indoor air concentration (attenuation factor) of the dwelling space. Mills et al. (68) considered two parallel CSTs connected to the third CST in series. This special case represented a basement and a crawl space both considered intrusion routes to the dwelling space above.

In general, the greatest problem in calculating indoor air concentration is the uncertainty in indoor exchange rate, which makes it difficult to obtain accurate indoor air concentration based solely on VI models. The measurement of indoor air concentration is still argued by some to be the only reliable method of site investigation, though this can also lead to orders of magnitude variation in nominally similar scenarios due to spatial and temporal variability or background sources (99). To avoid this, an empirical attenuation factor, "diffusion factor", is used to obtain indoor air concentration estimates in some models, such as in DF Sweden (100) and DF Norway (101–102), while, again, some (48–49) have suggested that indoor air concentration calculations be replaced by contaminant mass entry rate estimates. However, estimation of an indoor air concentration (or attenuation factor) offers a more direct feel of the hazard associated with the vapor intrusion process, no matter if calculated or measured. Table 6 summarizes some of the different assumption made in different VI modeling studies that make indoor air contaminant concentration estimates.

VI screening tools as models of the process

In VI site investigation, the focus is the indoor air concentration (and related attenuation factors) (30, 99), since this most directly affects the health of the residents in the buildings of concern. The general structure of typical 1-D screening tools is that the contaminant mass

flow rate in the soil must equal the contaminant mass rate entry into the building unless consumed by biodegradation (28, 35–37, 42–45). In other words, building operational conditions might be able to affect the soil gas transport (and soil vapor concentration profile), contrary to what is known from 3-D modeling (21–22).

For buildings with basements or built slab-on-grade, a slab crack is often assumed to be the main intrusion pathway (25). To satisfy the above mass conservation requirement, the crack must be assumed to be the sink for all the contaminant mass released by a certain source area at the bottom of the model domain. On the other hand, open ground surface communicating with atmosphere often exists around the building in many real cases, and in the setting assumed in many 1-D screening tools (28, 36, 68). In such a scenario involving a groundwater contaminant source and building of concern surrounded by open ground, the general contaminant soil gas concentration profile is actually determined by the diffusion from groundwater source to open surface, as modified by the existence of a building foundation due to the lateral blocking effect, as shown in Figure 1. It is not a surprise to see that the atmosphere plays a more significant role in determining contaminant soil gas concentration profile around the building than do the foundation cracks, which present a much smaller area for soil gas flow. A 1-D model cannot possibly capture the real situation depicted in Figure 1, because concentration variations in the x-z direction are not allowed. Hence these models, by virtue of requiring that contaminant mass conservation be satisfied at the foundation, use a different set of physical criteria to establish the subsurface concentration profiles. These may or may not result in accurate representation of the actual mass entry rate into the structure.

Figure 2 shows the nature of the problem quantitatively. This figure compares the contaminant mass entry rate into a building, calculated using a full 3-D numerical analysis to the contaminant release rate from a source directly beneath the building. In a 1-D analysis, this latter quantity is essentially what is represented as the mass entry rate, as a result of mass conservation.

What is clear from Figure 2 is that for low permeability soils ($k < 10^{-12} \text{ m}^2$) the 1-D approach would over predict the entry rate, especially for slab-on-grade construction. This is because the role of lateral contaminant diffusion away from beneath the foundation cannot properly be captured in 1-D models.

When soil permeability increases, the role of advection near the foundation increases, and this begins to drive the solution in the direction assumed in 1-D modeling – that is, a contaminant that makes it to beneath the foundation will be drawn into the structure by the advective flow (here driven by a typical -5 Pa internal depressurization). For very permeable soils ($k = 10^{-10} \text{ m}^2$), contaminant can actually be drawn towards the building, even if it did not originate beneath it.

The literature is somewhat divided on the ability of simple 1-D models to capture real results from the field. Hulot et al. (105) reported both soil gas and indoor air concentration were under-predicted by the J-E model and VOLASOIL in a field study in France. In that study, the VOLASOIL model was extended by the authors to include buildings with concrete slab. In another study by Hers et al. (106), the predictions by the J-E model were reported to be conservative, up to one or two orders of magnitude too high, consistent with Figure 2. In Provoost et al. (107), the accuracy of seven VI screening tools was investigated with data from buildings of slab-on-grade construction at 3 sites, and prediction were reported to be scattered within three orders of magnitude around the measurement for indoor air concentration. But there was a general over 11 prediction of soil gas concentration. Many possible alternative explanations were offered by Provoost et al. (107), but again, the

concern above trying to capture 3-D phenomena with 1-D models must be added. In another study by Provoost et al. (108), a similar conclusion was drawn based on a comparison among the above seven VI screening tools with other data from 7 sites. Most screening tools were again found to overpredict both soil and indoor contaminant concentrations, except for the J-E model, and Vlier-Humaan models, which slightly underestimated values. Thus Provoost et al. (108) actually recommended against use of these latter models as screening tools, due to the danger of false negatives.

Figure 2 may help to understand the different judgments made regarding 1-D models in different cases, due to the sensitivity of results to soil permeability. Again, there are a host of other parameters that have also been cited by the above authors as potential sources of uncertainty. What this brief analysis intends to convey is that 1-D models should not be looked to as “accurate” portrayals of the processes, even if in certain cases they might provide reasonable estimates of indoor air concentration.

Again, it is also important to re-emphasize the importance of one input parameter that really entirely outside the realm of VI modeling – the indoor air exchange rate. It is quite apparent that this parameter can greatly influence indoor air concentration predictions. As noted, Johnson (31) suggested the original J-E model (28) be modified by using an empirical air

exchange/soil gas entry rate ratio ($\frac{Q_s}{V_b A_e}$) to replace both the widely used Nazaroff equation (27), which has been used to calculate soil gas entry rate through a perimeter crack (Q_s), and indoor air exchange rate (A_e), independent parameters in the original J-E model (28). In other words, an empirical subslab-to-indoor air concentration attenuation factor was recommended to replace the previously assumed mass conservation, which tied the diffusive flux from source to building foundation to the contaminant mass entry rate through a crack.

Summary

The simulation of vapor intrusion from a subsurface source has been the focus of many recent studies due to the potential risk to human health that it describes. The following are general observations from the many recent studies of the problem.

- 3-D numerical simulation, although powerful, and applicable to scenarios involving complicated model domain and boundaries, multi-species transport and possible reaction and equilibrium processes, requires some significant computational effort. 1-D screening level tools, which are easy to use, can only be used describe simplified cases and often lack accuracy due to the required simplifying assumptions. Some recent efforts have used 3-D simulation to revisit computationally simple screening tools, in an effort to improve the latter’s accuracy, and have some shown possibilities for doing so.
- Biodegradation has been demonstrated to play a significant role in subslab concentration attenuation in certain situations. Reaction mechanism and kinetics are still not well understood and no agreement has been reached on how best to include these effects in VI models.
- There remains a lack of formal validation of any VI modeling. The difficulty arises from a lack of detailed enough characterization of real field sites to allow definitive assignment of the many parameters of modeling importance. There seems to be little debate regarding what processes need to be reflected in the models, but only limited confidence in the ability of even the most sophisticated 3-D models to accurately predict contaminant entry rates, and even less confidence in their ability to predict indoor air contaminant concentrations. It is understandable that in the absence of a reliable validated computational tool, the VI community will continue

to accept and rely on what might be slightly conservative screening tools that help to decide on whether to conduct what some feel is an inevitable indoor air sampling round to establish actual hazard. Nonetheless, there remains a strong interest in developing more accurate detailed models not only because they can serve to better delineate what field investigative work might be appropriate, but also because they can, if available, serve as a design basis for mitigation or remediation strategies.

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Literature cited

1. Tillman, FD.; Weaver, JW. Review of recent research on vapour intrusion. Washington, DC 20460: U. S. Environmental Protection Agency, Office of Research and Development; 2005. report EPA/600/R-05/106.
2. Turczynowicz L, Robinson NI. Exposure assessment modelling for volatiles - Towards an Australian indoor vapour intrusion model. *J. Toxicol. Env. Heal. A*. 2007; 70:1619–1634.
3. Provoost, J.; Tillman, FD.; Weaver, JW.; Reijnders, L.; Bronders, J.; Van Keer, I.; Swartjes, F. Vapour intrusion into buildings – a literature review. In: Daniels, JA., editor. *Advances in Environmental Research*. Vol. Volume 5. New York: Nova Science Publishers; 2010. p. 1-43.
4. Jury WA, Spencer WF, Farmer WJ. Behavior assessment model for trace organics in soil: I. Model description. *J. Environ. Qual.* 1983; 12(4):558–564.
5. Jury WA, Farmer WJ, Spencer WF. Behavior assessment model for trace organics in soil: II. Chemical classification and parameter sensitivity. *J. Environ. Qual.* 1984; 13(4):567–572.
6. Jury WA, Spencer WF, Farmer WJ. Behavior assessment model for trace organics in soil. III. Application of screening model. *J. Environ. Qual.* 1984a; 13(4):573–579.
7. Jury WA, Spencer WF, Farmer WJ. Behavior assessment model for trace organics in soil. IV. Review of experimental evidence. *J. Environ. Qual.* 1984b; 13(4):580–586.
8. Loureiro, CO. Ph.D. Dissertation. Berkeley, CA: Lawrence Berkeley Laboratory; 1987. Simulation of the steady-state transport of radon from soil into houses with basements under constant negative pressure. LBL-24378;
9. Loureiro CO, Abriola LM, Martin JE, Sestro RG. Three dimensional simulation of radon transport into houses with basements under constant negative pressure. *Environ. Sci. Technol.* 1990; 24(9): 1338–1348.
10. Mowris RJ, Fisk WJ. Modeling the effects of exhaust ventilation on ²²²Rn entry rates and indoor ²²²Rn concentrations. *Health Phys.* 1988; 54(5):491–501. [PubMed: 3360603]
11. Nazaroff WW, Feustel H, Nero AV, Revzan KL, Grimsrud DT. Radon transport into a detached one-story house with a basement. *Atmos. Environ.* 1985; 19(1):31–46.
12. Lindstrom FT, Boersma L, Gardiner H. 2,4-D diffusion in saturated soils. A mathematical theory. *Soil Sci.* 1968; 106(2):107–113.
13. Oddson JK, Letey J, Weeks LV. Predicted distribution of organic chemicals in solution and adsorbed as a function of position and time for various chemicals and soil properties. *Soil. Science Society of America Proceedings*. 1970; 34(3):412–417.
14. US EPA. 2012. <http://www.epa.gov/pesticides/factsheets/chemicals/ddt-brief-history-status.htm>
15. Clements WE, Wilkening MH. Atmospheric pressure effects on ²²²Rn transport across the earth-air interface. *J. Geophys. Res.* 1974; 79:5025–5029.
16. Schery SD, Gaeddert DH, Wilkening MH. Factors affecting exhalation of radon from a gravelly sandy loam. *J. Geophys. Res.* 1984; 89:7299–7309.

17. Robinson AL, Sextro RG. The influence of a subslab gravel layer and open area on soil-gas and radon entry into two experimental basement. *Health Phys.* 1995; 69:367–377. [PubMed: 7635733]
18. Garbesi K, Sextro RG, Robinson AL, Wooley JD, Owens JA, Nazaroff WW. Scale dependence of soil permeability to air: measurement method and field investigation. *Water Resour. Res.* 32(3): 547–560.
19. Garbesi K, Robinson AL, Sextro RG, Nazaroff WW. Radon entry into the houses: the importance of scale –dependent permeability. *Health Phys.* 1999; 77:183–191. [PubMed: 12877340]
20. Johnson PC, Kemblowski MW, Johnson RL. Assessing the significance of subsurface contaminant vapor migration to enclosed spaces: site-specific alternatives to generic estimates. *J. Soil Contam.* 1999; 8(3):389–421.
21. Abreu LDV, Johnson PC. Effect of vapor source-building separation and building construction on soil vapor intrusion as studied with a three-dimensional numerical model. *Environ. Sci. Technol.* 2005; 39(12):4550–4561. [PubMed: 16047792]
22. Yao Y, Pennell KG, Suuberg EM. Estimation of contaminant subslab concentration in vapor intrusion. *J. Hazard. Mater.* 2012; 231–232:10–17.
23. Nazaroff WW. Radon transport from soil to air. *Rev. Geophys.* 1992; 30(2):137–160.
24. Gadgil AJ. Models of radon entry. *Radiat. Prot. Dosim.* 1992; 45:373–380.
25. Robinson AL, Sextro RG. Radon Entry into Buildings Driven by Atmospheric Pressure Fluctuations. *Environ. Sci. Technol.* 1997; 31(6):1742–1748.
26. Andersen CE. Numerical modelling of radon-222 entry into houses: an outline of techniques and results. *Sci. Total Environ.* 2001; 272:33–42. [PubMed: 11379929]
27. Nazaroff WW. Predicting the rate of 222Rn Entry from soil into basement of a dwelling due to pressure-driven air flow. *Radiat. Prot. Dosim.* 1988; 24:199–202.
28. Johnson PC, Ettinger RA. Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. *Environ. Sci. Technol.* 1991; 25(8):1445–1452.
29. U.S. EPA. Office of Solid Waste and Emergency Response (OSWER). Draft of the guidance for evaluating the vapor intrusion to indoor air pathway from groundwater soils (subsurface vapor intrusion guidance). 2002 Nov 29.
30. U.S. EPA. Office of Solid Waste and Emergency Response (OSWER). U.S. EPA’s vapor intrusion database: preliminary evaluation of attenuation factors. 2008 Mar 4.
31. Johnson PC. Identification of application-specific critical inputs for the 1991 Johnson and Ettinger vapor intrusion algorithm. *Ground Water Monit. Rem.* 2005 winter;25(1):63–78.
32. Millington RJ, Quirk JM. Permeability of porous solids. *Trans. Faraday Soc.* 1961; 57:1200–1207.
33. Atteia O, Hohener P. Semianalytical model predicting transfer of volatile pollutant from groundwater to the soil surface. *Environ. Sci. Technol.* 2010; 44(16):6228–6232. [PubMed: 20704220]
34. Little JC, Daisy JM, Nazaroff WW. Transport of subsurface contaminants into buildings: an exposure pathway for volatile organics. *Environ. Sci. Technol.* 1992; 26(11):2058–2066.
35. Daugherty, SJ. Regulatory approaches to hydrocarbon contamination from underground storage tanks. In: Kostecki, PT.; Calabrese, EJ., editors. *Hydrocarbon Contaminated Soils and Groundwater*. Vol. Volume 1. Chelsea, MI: Lewis Publishers; 1991. p. 23-63.
36. Park HS. A method for assessing soil vapour intrusion from petroleum release sites: Multi-phase/ multi-fraction partitioning. *Global Nest J.* 1:195–204.
37. Van den Berg, R. Human exposure to soil Contamination: a qualitative and quantitative analysis towards proposals for human toxicological intervention values. Bilthoven, The Netherlands: RIVM; 1994. Report 725201011.
38. Yao Y, Suuberg EM. Estimation of contaminant subslab concentration in vapor intrusion including lateral source-building separation. In preparation.
39. Wright, J.; Howell, M. Evaluation of vapour migration modelling in quantifying exposure. *Proceedings Enviro04*. Sydney: 2004 Mar. paper No. e4194
40. Lowell PS, Eklund B. VOC emission fluxes as a function of lateral distance from the source. *Environ. Prog.* 2004; 23(1):52–58.

41. Symms, KG., et al. Modelling VOC migration and vapour intrusion into building indoor air from subsurface soil sources. In: Van den Brink, WJ.; Bosman, BR.; Arendt, F., editors. Contaminated Soil. Netherlands: Kluwer Academic Publishers; 1995. p. 551-556.
42. Murphy BL, Chan WR. A multi-compartment mass transfer model applied to building vapor intrusion. *Atmos. Environ.* 2011; 45(37):6650–6657.
43. Waitz, MFW.; Freijer, JI.; Kreule, P.; Swartjes, FA. The VOLASOIL risk assessment model based on CSOIL for soils contaminated with volatile compounds. Bilthoven, The Netherlands: RIVM; 1996. Report 715810014.
44. Bakker J, Lijzen JPA, van Wijnen HJ. Site-specific human risk assessment of soil contamination with volatile compounds. 2008 RIVM report 711701049.
45. Brand, E.; Otte, PF.; Lijzen, JPA. CSOIL 2000: an exposure model for human risk assessment of soil contamination. Bilthoven, The Netherlands: RIVM; 2007. Report 711701054.
46. Bozkurt, O. Ph.D. Dissertation. Providence, RI: Brown University; 2009. Investigation of vapor intrusion scenarios using a 3D numerical model.
47. Bozkurt O, Pennell KG, Suuberg EM. Simulation of the vapor intrusion process for nonhomogenous soils using a three-dimensional numerical model. *Ground Water Monit. Rem.* 2009; 29(1):92–104.
48. Pennell KG, Bozkurt O, Suuberg EM. Development and application of a three-dimensional finite element vapor intrusion model. *J. Air & Waste Manage. Assoc.* 2009; 59(4):447–460.
49. Yao Y, Shen R, Pennell KG, Suuberg EM. A comparison of the Johnson-Ettinger vapor intrusion screening model predictions with full three-dimensional model results. *Environ. Sci. Technol.* 2011; 45(12):2227–2235. [PubMed: 21344848]
50. Abreu, LDV. Ph.D. Dissertation. Tempe, AZ: Arizona State University; 2005. A transient three-dimensional numerical model to simulate vapor intrusion into buildings.
51. Yao Y, Pennell KG, Suuberg EM. The influence of transient processes on vapor intrusion processes. *Air and Waste Management Association-Vapor intrusion.* 2010; (1):186–210.
52. BP. Risc v4.03—risk assessment model for soil and groundwater applications, user's manual. Sunbury: BP Oil International; 2001.
53. Carslaw, HM.; Jaeger, JC. Conduction of heat in solids. Oxford: Clarendon; 1959.
54. Yao Y, Pennell KG, Suuberg EM. Vapor intrusion in urban settings: effect of foundation features and source location. *Procedia Environ. Sci.* 2011; 4:245–250.
55. Hers, I.; Zapf-Gilje, R. Canadian consortium research project - field validation of soil gas transport to indoor air pathway. Proceedings of the 1998 Petroleum Hydrocarbons and Organic Chemicals in Groundwater: National Groundwater Water Association; Houston Texas. 1998. p. 251-266.
56. Lahvis MA, Baehr AL, Baker RJ. Quantification of aerobic biodegradation and volatilization rates of gasoline hydrocarbons near the water table under natural attenuation conditions. *Water Resour. Res.* 1999; 35(3):753–765.
57. Roggemans, S. M.S. Thesis. Arizona State University; 1998. Natural attenuation of hydrocarbon vapors in the vadose zone.
58. Ficher ML, Bentley AJ, Dunkin KA, Hodgson AT, Nazaroff WW, Sextro RG, Daisey JM. Factors affecting indoor air concentrations of volatile organic compounds at a site of subsurface gasoline contamination. *Environ. Sci. Technol.* 1996; 30(10):2948–2957.
59. Fitzpatrick, NA.; Fitzgerald, JJ. presented at the 11th Annul. Conf. on Contaminated Soils. Amherst: University of Massachusetts; 1996 Oct. An evaluation of vapor intrusion into buildings through a study of field data. <http://www.state.ma.us/dep/bwsc/miscpubs.htm>
60. Ostendorf DW, Kampbell DH. Biodegradation of hydrocarbon vapors in the unsaturated zone. *Water Resour. Res.* 1991; 27(4):453–462.
61. Luo H, Dahlen P, Johnson PC, Peargin T, Creamer T. Spatial variability of soil-gas concentrations near and beneath a building overlying shallow petroleum hydrocarbon-impacted soils. *Ground Water Monit. Rem.* 2009; 29(1):81–91.
62. Patterson BM, Davis GB. Quantification of vapor intrusion pathways into a slab-on-ground building under varying Environmental Conditions. *Environ. Sci. Technol.* 2009; 43(3):650–656. [PubMed: 19244997]

63. Ellis, DE., et al. Remediation technology forum intrinsic remediation project at Dover Air Force Base, Delaware. Symposium on Natural Attenuation of Chlorinated Organics in Ground Water; USEPA; September 11–13; Dallas, TX. 1996. EPA/540/R-96/509.
64. Ririe, GT.; Sweeney, RE. Fate and transport of volatile hydrocarbons in the vadose zone. Proc. NGWA/API Conf. Petrol. Hydrocarbons Org. Chem. in Groundwater: Prevention, Detection, and Restoration; Houston, TX. 1996. p. 529-542.
65. Lahvis MA, Baehr AL. Documentation of R-UNSAT, a computer model for the simulation of reactive, multispecies transport in the unsaturated zone. 1997 U.S. Geological Open-File Report 97–630.
66. Davis GB, Rayner JL, Trefry MG, Fisher SJ, Patterson BM. Measurement and modeling of temporal variations in hydrocarbon vapor behavior in a layered soil profile. *Vadose Zone J.* 2005; 4:225–239.
67. Jeng, CY.; Kremesec, VJ.; Primack, HS. Proceedings of 1996 Petroleum Hydrocarbon and Organic Chemicals in Ground Water. Houston, Texas: API/NGWA; 1996. Models of hydrocarbon vapor diffusion through soil and transport into buildings; p. 319-338.
68. Mills WB, Liu S, Rigby MC, Brenner D. Time-variable simulation of soil vapor intrusion into a building with a combined crawl space and basement. *Environ. Sci. Technol.* 2007; 41(14):4993–5001. [PubMed: 17711214]
69. Sanders PA, Stern AH. Calculation of soil cleanup criteria for carcinogenic volatile organic chemicals as controlled by the soil-to-indoor air exposure pathway. *Environ. Toxicol. Chem.* 1994; 13(8):1367–1373.
70. Ünlü K, Kemblowski MW, Parker JC, Stevens D, Chong PK, Kamil I. A screening model for effects of land-disposed wastes on groundwater quality. *J. Contam. Hydrol.* 1992; 11:27–49.
71. Van Genuchten M Th, Davidson JM, Wierenga PJ. An evaluation of kinetic and equilibrium equations for the prediction of pesticide movement through porous media. *Soil Sci. Soc. Am. Proc.* 1974; 38:29–34.
72. Van Genuchten M Th, Wierenga PJ. Mass transfer in sorbing porous media. I. Analytical solutions. *Soil Sci. Soc. Am. J.* 1976; 40:473–480.
73. Van Genuchten M Th, Wierenga PJ. Mass transfer in sorbing porous media. II experimental evaluation with tritium. *Soil Sci. Soc. Am. J.* 1977; 41:272–278.
74. Van Genuchten M Th, Wierenga PJ, O'Connor GA. Mass transfer in sorbing porous media. III. Experimental evaluation with 2,4,5-T. *Soil Sci. Soc. Am. J.* 1977; 41:278–285.
75. Anderssen FR, de Hoog FR, Markey BR. Modelling the volatilization of organic soil contaminants: Extension of the Jury, Spencer and Farmer behaviour assessment model and solution. *Appl. Math. Lett.* 1997; 10(1):31–34.
76. Turczyowicz L, Robinson N. A model to derive soil criteria for benzene migrating from soil to dwelling interior in homes with crawl spaces. *Hum. Ecol. Risk Assess.* 2001; 7(2):387–415.
77. Lin JS, Hildemann LM. Nonsteady-state analytical model to predict gaseous emissions of volatile organic compounds from landfills. *J. Hazard. Mater.* 1995; 40(3):271–295.
78. Roggemans, S.; Bruce, CL.; Johnson, PC. API Technical Bulletin No. 15. Washington, DC: American Petroleum Institute; 2002. Vadose zone natural attenuation of hydrocarbon vapors: an empirical assessment of soil gas vertical profile data.
79. Devaull GE. Indoor vapor intrusion with oxygen-limited biodegradation for a subsurface gasoline source. *Environ. Sci. Technol.* 2007; 41(9):3241–3248. [PubMed: 17539532]
80. Parker JC. Modeling volatile chemical transport, biodecay, and emission to indoor air. *Ground Water Monit. Rem.* 2003; 23(1):107–120.
81. Verginelli I, Baciocchi R. Modeling of vapor intrusion from hydrocarbon-contaminated sources accounting for aerobic and anaerobic biodegradation. *J. Contam. Hydrol.* 2011; 126:167–180. [PubMed: 22115083]
82. Hers J, Atwater JW, Zapf-Gilje R, Li L. Evaluation of vadose zone biodegradation of BTX vapours. *Journal of Contaminant Hydrogeology.* 2000; 46(3–4):230–264.
83. Talimcioglu, NM. Ph.D. thesis. Hoboken, NJ, USA: Stevens Institute of Technology; 1991. A model for evaluation of the impact of contaminated soil on groundwater.

84. Korfiatis, GP.; Talimcioglu, NM. Model for evaluation of the impact of contaminated soil on groundwater. Hoboken, NJ, USA: Stevens Institute of Technology; 1991. Final report.
85. Korfiatis, GP.; Talimcioglu, NM. IMPACT: a model for calculation of soil cleanup levels. Spring: Remediation; 1994. p. 175-188.1994
86. Yao, Y. Ph.D. Dissertation. Providence, RI: Brown University; 2012. Modeling vapor intrusion - the influence of biodegradation and useful approximation techniques.
87. Abreu LDV, Johnson PC. Modeling the effect of aerobic biodegradation on soil vapor intrusion into buildings - influence of degradation rate, source concentration, and depth. Environ. Sci. Technol. 2006; 40(7):2304–2315. [PubMed: 16646467]
88. Abreu LDV, Ettinger R, McAlary T. Simulated soil vapor intrusion attenuation factors including biodegradation for petroleum hydrocarbons. Ground Water Monit. Rem. 2009 winter;29(1):105–117.
89. Yu S, Unger AJA, Parker B. Simulating the fate and transport of TCE from groundwater to indoor Air. J. Contam. Hydrol. 2009; 107(3–4):140–161. [PubMed: 19525028]
90. Van Cenuchten M Th, Alves AJ. Analytical solutions of the one-dimensional convective-dispersive solute transport equation. United States Department of Agriculture. 1982 technical bulletin 1661.
91. Ribbons, DW.; Eaton, RW. Chemical transformations of aromatic hydrocarbons that support the growth of microorganisms. In: Mitchell, R., editor. Environmental Microbiology. New York, NY: Wiley-Liss Publishers; 1992.
92. Wiedemeier, T.; Wilson, JT.; Kampbell, DH.; Miller, RN.; Hansen, JE. Technical protocol for implementing intrinsic remediation with long-term monitoring for natural attenuation of fuel contamination dissolved in groundwater. Vol. Volume 1. San Antonio, TX: Air Force Center for Environmental Excellence, Technology Transfer Division Brooks AFB; 1995.
93. Borden RC, Bedient PB. Transport of dissolved hydrocarbons influenced by oxygen-limited biodegradation: 1. Theoretical development. Water Resour. Res. 1986; 22(13):1973–1982.
94. Sanders PF, Talimcioglu NM. Soil-to-indoor air exposure models for volatile organic compounds: the effect of soil moisture. Environ. Toxicol. Chem. 1997; 16(12):2597–2604.
95. Andersen, CE. Entry of soil gas and radon into houses. RisøR-623 ŽEN. Denmark: Risø National Laboratory, DK-4000 Roskilde; 1992.
96. Ferguson CC, Krylov VV, McGrath PT. Contamination of indoor air by toxic soil vapors: a screening risk assessment model. Building Environ. 1995; 30(3):375–383.
97. Nazaroff WW, Lewls SR, Doyle SM, Moed BA, Nero AV. Experiments on pollutant transport from soil into residential basements by pressure-driven airflow. Environ. Sci. Technol. 1987; 21(5):459–466. [PubMed: 22296133]
98. Krylov VV, Ferguson CC. Contamination of indoor air by toxic soil vapors: the effects of subfloor ventilation and other protective measures. Building Environ. 1998; 33(6):331–347.
99. U.S. EPA. Office of Solid Waste and Emergency Response (OSWER). EPA’s vapor intrusion database: evaluation and characterization of attenuation factors for chlorinated volatile organic compounds and residential buildings. 2012 Mar 16.
100. Naturvadsverket. Model and data used for generic guideline values for contaminated soils in Sweden. Stockholm, Sweden: Swedish Environmental Protection Agency; 1996. Development of generic guideline values. NV Report No. 4639
101. SFT. Management for contaminated land: preliminary guidelines for executive procedures, report 97:01. Oslo: Norwegian Pollution Control Authority; 1995. ISBN 82-7655-030-4.
102. SFT. Management of contaminated land, report 99:06. Oslo: Norwegian Pollution Control Authority; 1999. ISBN 82-7655-192-0.
103. Olson D, Corsi RL. Characterizing exposure to chemicals from soil vapor intrusion using a two compartment model. Atmos. Environ. 2001; 35(24):4201–4209.
104. Olson D, Corsi RL. Fate and Transport of Contaminants in Indoor Air. Soil Sediment Contam. 2002; 11(4):583–601.
105. Hulot, C.; Hazebrouck, B.; Gay, G.; Malherbe, L.; Pokryszka, Z. Conference “CONSOIL,”. Ghent, Belgium: 2003 May. Vapor emissions from contaminated soils into buildings: Comparison between predictions from transport models and field measurements; p. 1-9.

106. Hers I, Zapf-Gilje R, Evans D, Li L. Comparison, validation, and use of models for predicting indoor air quality from soil and groundwater contamination. 2002; 11(4):491–527.
107. Provoost J, Reijnders L, Swartjes F, Bronders J, Seuntjens P, Lijzen J. Accuracy of seven vapour intrusion algorithms for VOC in groundwater. J Soils Sediments. 2009; 9(1):62–73.
108. Provoost J, Bosman A, Reijnders L, Bronders J, Touchant K, Swartjes F. Vapour intrusion from the vadose zone-----seven algorithms compared. J Soils Sediments. 2010; 10:473–483.

FIGURE 1.

Simulated contaminant concentration profile based on ASU 3-D numerical model (α is groundwater source vapor-to-indoor air contaminant concentration attenuation factor and Q_s is soil gas entry rate) (21).

FIGURE 2.

3-D simulation results on the contaminant entry rate to sub-structure release rate for 2m (solid points) and 0.1m (open points) depth foundations. The values in the legend refer source depth (m) and results are shown for various soil permeabilities (k). M_{ck} refers to the mass entry rate through a foundation crack, and $M_{released}$ is total contaminant release from the source lying directly beneath the building footprint (49). Any ordinate value different from unity indicates that one basic assumption of 1-D models will lead to errors in estimates of contaminant entry rate.

TABLE 1

The summary of contaminant soil vapor transport models without biodegradation.

Main governing equation	Examples of model use
Steady state advection $0 = -\nabla \cdot (q_g c_{ig}) \quad (6)$	Little et al. (#3) (34)
Steady state diffusion $0 = \nabla^2 c_{ig} \quad (7)$	OCHCA (35), J-E model (28), Park (36), CSOIL (37), Atteia and Hohener (33), Yao et al. (22) ² , Yao and Suuberg (38) ² , Wrighter and Howell (39), Lowell and Eklund (40) ²
Transient diffusion $\phi_{g,w,s} \frac{c_{ig}}{t} = \nabla^2 c_{ig} \quad (8)$	Little et al. (#1, 2 model) (34) Symms et al. (41)
Steady state uniform advection & diffusion $q_g \nabla c_{ig} = \nabla \cdot (D_i \nabla c_{ig}) \quad (9)$	Murphy and Chan (42), VOLASOIL (43–44), CSOIL 2000 (45)
Steady state advection & diffusion $\nabla \cdot (q_g c_{ig}) = \nabla \cdot (D_i \nabla c_{ig}) \quad (10)$	The Brown model (Bozkurt (46) ³ⁿ , Bozkurt et al. (47) ³ⁿ , Pennell et al. (48) ³ⁿ , Yao et al. (49) ³ⁿ), The ASU model (Abreu (50) ³ⁿ , Abreu and Johnson (21) ³ⁿ)
Transient advection & diffusion $\phi_{g,w,s} \frac{c_{ig}}{t} = -\nabla \cdot (q_g c_{ig}) + \nabla \cdot (D_i \nabla c_{ig}) \quad (11)$	The Brown model (Yao et al. (51) ³ⁿ),

Note: while some models were developed in more complete form, what is show here is how the models were actually used in the indicated references. **2(3)n** means 2(3)-D numerically solved models; models shown without superscript symbols are all 1-D, steady state, analytical models

TABLE 2

The summary of contaminant soil vapor transport models including biodegradation.

Governing equation	Models
Steady state diffusion & biodegradation (1 species) $0 = \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (22)$	Ririe and Sweeney (64), R-UNSAT (65), Johnson et al. (20), Davis et al. (66)
Transient diffusion & biodegradation (1 species) $\phi_{g,w,s} \frac{c_{ig}}{t} = - \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (23)$	Jeng et al. (67), VIM (68), Sanders and Stern (#1) (69)
Constant convection & transient diffusion & biodegradation (1 species) $\phi_{g,w,s} \frac{c_{ig}}{t} = - q \nabla c_{ig} + \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (24)$	Ünlü et al. (70), Jury et al. (4–7), van Genuchten et al. (71–74), Sanders and Stern (#2) (69), Anderson et al. (75), T & R model (76), Lin and Hildemann (77)
Steady state diffusion & biodegradation (2 species) $0 = \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (25)$	Ostendorf and Kampbell (60), Roggemans et al. (57, 78), Devauld (79), Parker (80), Verginelli and Baciocchi (81)
Convection & diffusion & biodegradation (2 species) $\phi_{g,w,s} \frac{c_{ig}}{t} = - \nabla \cdot (q_g c_{ig}) + \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (26)$	R-UNSAT (64) ²ⁿ , VADBIO (82) ²ⁿ , IMPACT (83–85) ²ⁿ , The Brown model (Yao (86) ³ⁿ), The ASU model (Abreu and Johnson (87) ³ⁿ , Abreu et al. (88)), CompFlow Bio (89) ²ⁿ

Note: 2(3)ⁿ means 2(3)-D numerically solve model; models shown without superscript symbols are all 1-D, steady state, analytical models

TABLE 3

Summary of biodegradation kinetic expressions used in vapor intrusion models

Models	Reaction kinetics
R-UNSAT (64)	Zero, first order reaction, coupled O ₂
Sanders and Stern (69) / (#2 model)	First order reaction
Anderson et al. (75)	First order reaction
VADBIO (82)	First order reaction, piecewise zero and first order reaction, instant reaction, coupled O ₂
T & R model (76)	First order reaction
IMPACT (83–85)	First order reaction
VIM (68)	First order reaction
Ostendorf and Kampbell (60)	Monod reaction
Johnson et al. (20)	First order reaction
Roggemans et al. (78)	Instant reaction, coupled O ₂
Parker (80)	Zero order reaction, coupled O ₂
The ASU model (87–88)	Piecewise first order reaction, coupled O ₂
Devauil (79)	Piecewise first order reaction, coupled O ₂
The Brown Model (86)	Second order reaction, coupled O ₂
Verginelli and Baciocchi (81)	First order reaction for both aerobic and anaerobic, coupled O ₂

TABLE 4

Summary of assumed biodegradation rate constants in vapor intrusion models

Reaction kinetics	Models	Rate constants
Monod equation $\frac{dS}{dt} = \frac{V_{max}S}{S + K_m}$	Ostendorf and Kampbell (60)	Hydrocarbons: $V_{max} = (5.56 \sim 11.3) \times 10^{-9} \text{ kg/m}^3/\text{s}$ $K_m = (5.56 \sim 8.67) \times 10^{-4} \text{ kg/m}^3$
Zero order reaction $\frac{dS}{dt} = -k_0$	VADBIO (82)	BTX and fuel hydrocarbons $k_0 = (1.56 \sim 3.78) \times 10^{-7} \text{ kg/m}^3/\text{s}$
	Parker (80)	$k_0 = 1 \sim 10 \text{ mg/kg/day}$ (maximum decay rate)
	R-UNSAT (65)	k_1 (MTBE) = $1 \times 10^{-8} \text{ s}^{-1}$ k_1 (BTEX) = $(1 \sim 100) \times 10^{-7} \text{ s}^{-1}$
	IMPACT (83–85)	k_1 (VOC) = $4.46 \times 10^{-8} \sim 5.01 \times 10^{-7} \text{ s}^{-1}$
	VADBIO (82)	BTX and fuel hydrocarbons $k_1 = (1.39 \sim 3.33) \times 10^{-4} \text{ s}^{-1}$
First order reaction $\frac{dS}{dt} = -k_1 S$	T & R model (76)	k_1 (Benzene) = $1.93 \times 10^{-8} \text{ s}^{-1}$ in soil k_1 (Benzene) = $5.99 \times 10^{-7} \text{ s}^{-1}$ in air
	The ASU model (87–88)	k_1 (BTEX) = $(0.018 \sim 2) \times \text{h}^{-1}$ in water
	Devaul (79)	Aromatic hydrocarbons $k_1 = 9.14 \times 10^{-6} \text{ s}^{-1}$ in water Straight chain and branched aliphatic hydrocarbons $k_1 = 8.22 \times 10^{-4} \text{ s}^{-1}$ in water
	Verginelli and Baciocchi (81)	BTEX and other hydrocarbons $k_1 = 0.79 - 71 \text{ h}^{-1}$ for aerobic biodegradation $k_1 = 1.9 \times 10^{-4} - 1.55 \times 10^{-2} \text{ h}^{-1}$ for anaerobic biodegradation
Second order reaction $\frac{dS}{dt} = -k_2 S[O]$	The Brown model (86)	k_2 (Benzene) = $(1.79 \sim 179) \times 10^{-5} \text{ m}^3/\text{kg/s}$ in water
Where [O] is the oxygen concentration		

Note: (MTBE: Methyl tert-butyl ether; BTEX: benzene, toluene, ethylbenzene and xylene; BTX: benzene, toluene and xylene)

TABLE 5

The summary of entry processes used in vapor intrusion modeling.

Entry scenario	Models
<p>No-barrier entry</p>	Little et al. (#1,3) (34), Devaull (79), Jeng et al. (67), Sanders and Stern (#1) (69)
<p>Empirical diffusive layer resistance</p>	Little et al. (#2) (34), Sanders and Stern (#2) (69), VOLASOIL (43)
<p>No-barrier entry into crawl space</p>	CSOIL (37), CSOIL 2000 (45), VOLASOIL (43–44)
<p>Diffusive barrier into crawl space</p>	VOLASOIL (44), T & R model (76), IMPACT (83–85), VIM (68)
<p>Empirical slab attenuation</p>	OCHCA (35)

Entry scenario	Models
<div> <p>Permeable slab</p><p>Uniformly permeable slab</p></div>	Krylov and Ferguson (98), Ferguson et al. (96)
<div> <p>Crack</p><p>Foundation slab crack</p></div>	J-E model (28), Johnson et al. (20), Park (36), Murphy and Chan (42), The ASU model (Abreu and Johnson (21, 87) ³ⁿ , Abreu (50) ³ⁿ , Abreu et al. (88) ³ⁿ), The Brown model (Bozkurt et al. (46–47) ³ⁿ , Pennell et al. (48) ³ⁿ , Yao et al. (69) ³ⁿ , Parker (80), CompFlow Bio (89), VIM (68), VOLASOIL (44), Symms et al. (41), Verginelli and Baciocchi (81)

TABLE 6

The summary of indoor air concentration calculation assumptions.

Entry scenario	Models
<p>Dwelling Space</p> <p>Single CST</p>	<p>Little et al. (34), OCHCA (35), Sanders and Stern (69), J-E model (28), Johnson et al. (20), Jeng et al. (67), Parker (80), Devauil (79), CompFlow Bio (89), Verginelli and Baciocchi (81), The ASU model (Abreu and Johnson (21, 87)³ⁿ, Abreu (50)³ⁿ, Abreu et al. (88)³ⁿ), The Brown model (Bozkurt et al. (46–47)³ⁿ, Pennell et al. (48)³ⁿ, Yao et al. (49)³ⁿ),</p>
<p>Dwelling Space</p> <p>Basemnt</p> <p>Crawl space</p> <p>Series CSTs</p>	<p>T & R model (76), CSOIL (37), VOLASOIL (43–44), CSOIL 2000 (45), IMPACT (83–85), Murphy and Chan (42), Olson and Corsi (103–104), Ferguson et al. (96), Krylov and Ferguson (98)</p>
<p>Dwelling Space</p> <p>Basement</p> <p>Crawl space</p> <p>Combined series and parallel CSTs</p>	<p>VIM (68)</p>