

Indoor Air as a Source of VOC Contamination in Shallow Soils Below Buildings

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US EPA and many state regulatory agency guidance documents recommend below-foundation vapor sampling as a key element of site investigations to determine if vapor migration from underlying soil into buildings is a completed exposure pathway (USEPA, 2002; WIDHFS, 2003; San Diego County, 2004; PADEP, 2004). If volatile organic compounds (VOCs) are detected below the building foundation, then VOC migration from the subsurface is assumed to be occurring, and further investigation is needed to determine the extent of the VOC impact. These guidance documents are predicated on the assumption that VOCs detected in below-foundation samples have originated from deeper within the subsurface. However, detection of VOCs in below-foundation vapor samples alone is not sufficient to conclude that the VOCs are migrating from the subsurface upward towards a building. VOCs detected in below-foundation vapor samples can originate from indoor sources, migrating down through the slab by diffusion or advection. Commonly referenced conceptual models for vapor intrusion address VOC migration from the subsurface into buildings but do not consider the potential for VOC migration from buildings into the subsurface (USEPA, 2002; Johnson and Ettinger, 1991; Parker, 2003). The advective and diffusive forces that lead to the migration of VOCs from the subsurface into buildings are equally likely to result in the migration of VOCs from buildings into the subsurface when pressure or concentration gradients support such migration. In this paper we present: i) pressure gradient measurements indicating bi-directional advective flow across building foundations, ii) simple modeling indicating that indoor sources of VOCs may cause subsurface impacts through advection across the building foundation, and iii) field data from a site where indoor sources rather than subsurface contamination were the source of VOCs detected in below-foundation vapor samples.

Keywords Vapor intrusion, indoor air, subsurface migration

Introduction

Largely in response to the findings at two Colorado sites with chlorinated solvent groundwater plumes, the Corrective Action Branch of the Office of Solid Waste and Emergency Response (OSWER) at the US EPA developed and released a draft supplemental guidance in 2001 to evaluate the vapor intrusion to indoor air pathway at RCRA corrective action facilities (US EPA, 2001a). In 2002, the US EPA issued the *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* (“US EPA Vapor Intrusion Guidance,” US EPA, 2002), which superseded the draft 2001 guidance.

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Because modeling failed to identify the vapor intrusion impacts at the Colorado sites (Renner, 2002), the US EPA draft guidance documents have a reduced reliance on models for pathway screening and favor direct measurements to evaluate the potential for vapor intrusion at corrective action sites (Schuver, 2003). In addition, a number of state and local regulatory agencies have recently issued new or updated guidance that similarly emphasizes field measurements instead of modeling for the evaluation of the vapor intrusion pathway (WIDHFS, 2003; San Diego County, 2004; PADEP, 2004).

In its current form, the US EPA Vapor Intrusion Guidance (US EPA, 2002) recommends a tiered approach for evaluation of the vapor intrusion pathway at corrective action sites consisting of: i) a preliminary pathway evaluation based on the presence of a volatile source and receptor, ii) an evaluation of volatile organic compound (VOC) concentrations using generic and “semi-site-specific” screening concentrations, and iii) a site investigation to evaluate vapor intrusion by direct measurement and limited mathematical modeling. For a number of common VOCs such as trichloroethene (TCE) and benzene, both the generic and the “semi-site-specific” groundwater vapor intrusion screening limits proposed by the US EPA are equal to drinking water Maximum Contaminant Levels (i.e., 5 ug/L)—a “screening level” that is likely to screen out very few groundwater corrective action sites. As a result, a majority of corrective action sites where US EPA guidance is applied will require field-based site investigations to evaluate the potential for vapor intrusion impacts. However, site-specific evaluations of potential vapor intrusion, particularly those involving the measurement of indoor air VOC levels, can prove to be highly problematic due to the presence of common indoor sources of VOCs already present within buildings (McHugh *et al.*, 2004). Average background indoor air concentrations of many common VOCs in buildings located away from corrective action sites exceed US EPA screening concentrations for indoor air (see Table 1). Therefore, for VOCs associated with common indoor sources, the direct measurement of concentrations in indoor air is often not an effective method for identifying vapor intrusion impacts.

US EPA and many state regulatory agency guidance documents recommend below-foundation vapor sampling as a key element of site investigations to evaluate indoor air (US EPA, 2002; WIDHFS, 2003; San Diego County, 2004; PADEP, 2004). In an attempt to eliminate the confounding effect of indoor VOC sources, these guidance documents typically recommend below-foundation vapor sampling prior to sampling of indoor air (e.g., Page 38 of US EPA, 2002). If no VOCs are detected in the below-foundation vapor samples, then migration of VOCs from the subsurface through the building foundation is not considered to be a problem. However, if VOCs are detected in the below-foundation samples, then migration from the subsurface is assumed to be occurring, and further evaluation is required to determine the extent of the subsurface impact. These guidance documents are predicated on the assumption that VOCs detected in below-foundation samples have originated from deeper within the subsurface and are migrating towards the building. However, based on the results of modeling and field analyses, detection of VOCs in below-foundation samples is not sufficient to conclude that VOCs are migrating from the subsurface towards a building. In some cases, VOCs detected in below-foundation samples may have originated from indoor sources and are migrating downward through the building foundation by diffusion or advection.

Commonly referenced conceptual models of vapor intrusion address VOC migration from the subsurface into buildings but do not consider the potential for VOC migration from buildings into the subsurface (US EPA, 2002; Johnson and Ettinger, 1991; Parker, 2003). However, the advective and diffusive forces that lead to the migration of VOCs from the subsurface into buildings are equally capable of causing migration of VOCs from buildings

Table 1
Average background indoor air VOC concentration ug/m³

Chemical	US EPA (2002)							
	Brown <i>et al.</i> (1994)	Sheldon (1992)	EPA IAQ (1991)	Shah and Singh (1988)	Stolwijk (1990)	Foster <i>et al.</i> (2002)	Kurtz and Folkes (2002)	Sexton <i>et al.</i> (2004)
Benzene	8	2.2	14	16.5	10	4.1	—	5.8
Ethylbenzene	5	—	14	12.5	10	—	—	3.9
Toluene	37	—	61	27.8	80	—	—	22.4
Xylenes	24	—	14	—	30	—	—	19.2
Carbon Tetrachloride	—	0.5	5	2.5	20	—	—	0.60
Dichlorobenzene, 1,4-	8	1.0	58	23.8	5	—	—	1.2
Dichloroethane, 1,2-	—	—	—	—	—	0.07	0.05	—
Dichloroethene, 1,1-	—	—	—	—	—	—	<0.04	—
Methylene Chloride	17	15	—	—	—	0.98	—	7.8
Tetrachloroethene	7	0.3	28	20.7	5	1.6	1.1	2.9
Trichloroethane, 1,1,1-	—	—	70	—	10	0.70	1.0	—
Trichloroethene	—	—	9	7.2	5	0.15	0.16	0.50
Vinyl Chloride	—	—	—	—	—	0.01	0.02	—

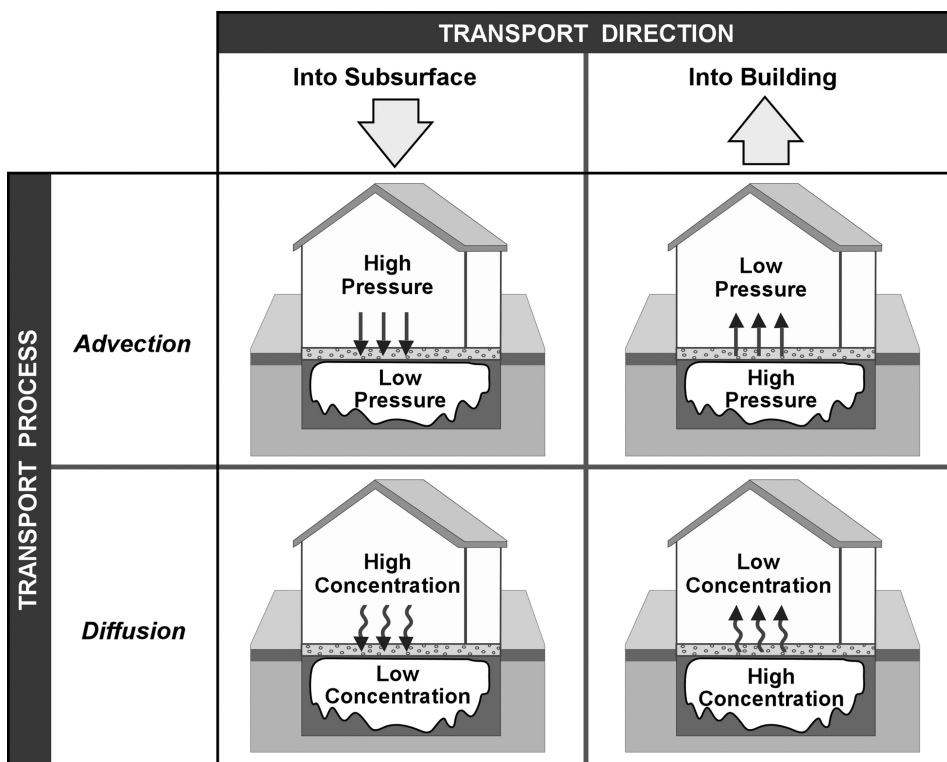


Figure 1. Conceptual model of cross-foundation VOC transport.

into the subsurface under conditions where pressure or concentration gradients support such migration (see Figure 1).

In this paper we present: i) pressure gradient measurements indicating bi-directional advective flow across building foundations, ii) simple analytical modeling indicating that indoor sources of VOCs may cause subsurface impacts through advection across the building foundation, and iii) field data from a site where indoor sources rather than subsurface contamination were the source of VOCs detected in below-foundation vapor samples.

Pressure Gradients across Building Foundations

Vapor migration between the indoor air of a building and the subsurface soil gas can occur by advection when there is a pressure differential between the building interior and the subsurface. Single family residential buildings are often under negative pressure due to a variety of factors that cause exfiltration of indoor air such as combustion sources, kitchen and bathroom ventilation, and the stack effect associated with indoor heating (US EPA, 2001b). However, current residential building design standards require the maintenance of a slightly positive building pressure by controlled outdoor air intake when dehumidification is required (ASHRAE, 2004). As a result, newer residences are more likely than older residences to operate with positive building pressures. In addition, larger buildings with central Heating, Ventilation, and Air-Conditioning (HVAC) systems are typically designed to operate under positive pressure (Bearg, 1993). In both cases, the pressure differential can vary over time under the influence of the building HVAC system, building temperature, wind conditions,

barometric pressure changes, and other factors, resulting in changes between positive or negative building pressures with respect to the below-foundation pressure. Negative building pressure supports advection from the subsurface into the building while positive building pressure supports advection from the building into the subsurface. Larger buildings may be more likely to experience pressure gradient reversals because environmental factors such as high wind or low ambient temperatures often decrease pressures leading to temporary negative pressure conditions in buildings that are typically operated under positive pressure.

To characterize pressure gradients that can occur across building foundations between the subsurface and indoor air, cross-foundation pressure gradients were characterized in three buildings in the Houston, Texas area: one commercial warehouse building and two single-family residential buildings. All three buildings were slab-on-grade construction. Building to below-foundation pressure gradients were measured using an Omega PX-274-01DI differential pressure transducer with a range of -125 to 125 Pa \pm 1%. The pressure gradient across the building foundations was measured by connecting the low pressure port to a sealed hole penetrating the slab and keeping the high pressure port open to the building atmosphere. In all three buildings, pressure gradient reversals between negative and positive building pressure were observed to occur within a single 24-hour monitoring period. Typical 24-hour periods for a residential building and a commercial warehouse building are shown in Figure 2. The observed cross-foundation pressure gradients recorded at the commercial warehouse building ranged from $+25$ Pa to -30 Pa, with lower pressure gradients generally observed in the two residential buildings. Although this is a limited dataset, the pressure gradient measurements indicate that both advective flow from the subsurface into a building and advective flow from a building into the subsurface can occur within a single 24-hour period in either residential or commercial buildings. Additional research would be required to determine the prevalence of these pressure reversals in residential and commercial buildings.

Development of Advective Transport Model

To evaluate the impact of variable pressure gradients on the transport of VOCs between a slab-on-grade building and the soil gas immediately below the building, we have developed a simple transient mixing model. For the purpose of simulating building/below-foundation air exchange, the model incorporates periodic oscillations between positive and negative building pressure. The advection model simulates vapor migration between two compartments as a result of this pressure oscillation: i) the building air space, and ii) subsurface soil gas immediately underlying the foundation slab. The model has been used to evaluate the impact of transient indoor VOC sources on the below-foundation air quality.

The variables in the advection model are shown in Figure 3. When the indoor air pressure is greater than the subsurface soil air pressure (a positive pressure condition), air flows from the building into the subsurface soil through the building foundation. Alternatively, when the indoor air pressure is less than the subsurface soil air pressure (a negative pressure condition), vapor flows into the building from the subsurface soil.

Key assumptions of the model are:

- Continuous and constant exchange occurs between the building and the ambient air (Q_{ab} and Q_{ba} are always greater than 0).
- Vapor exchange between the sub-foundation soils and adjacent soils is driven only by advective flow between the building and the sub-foundation (i.e., $Q_{bg} = Q_{ga}$ and $Q_{gb} = Q_{ag}$).

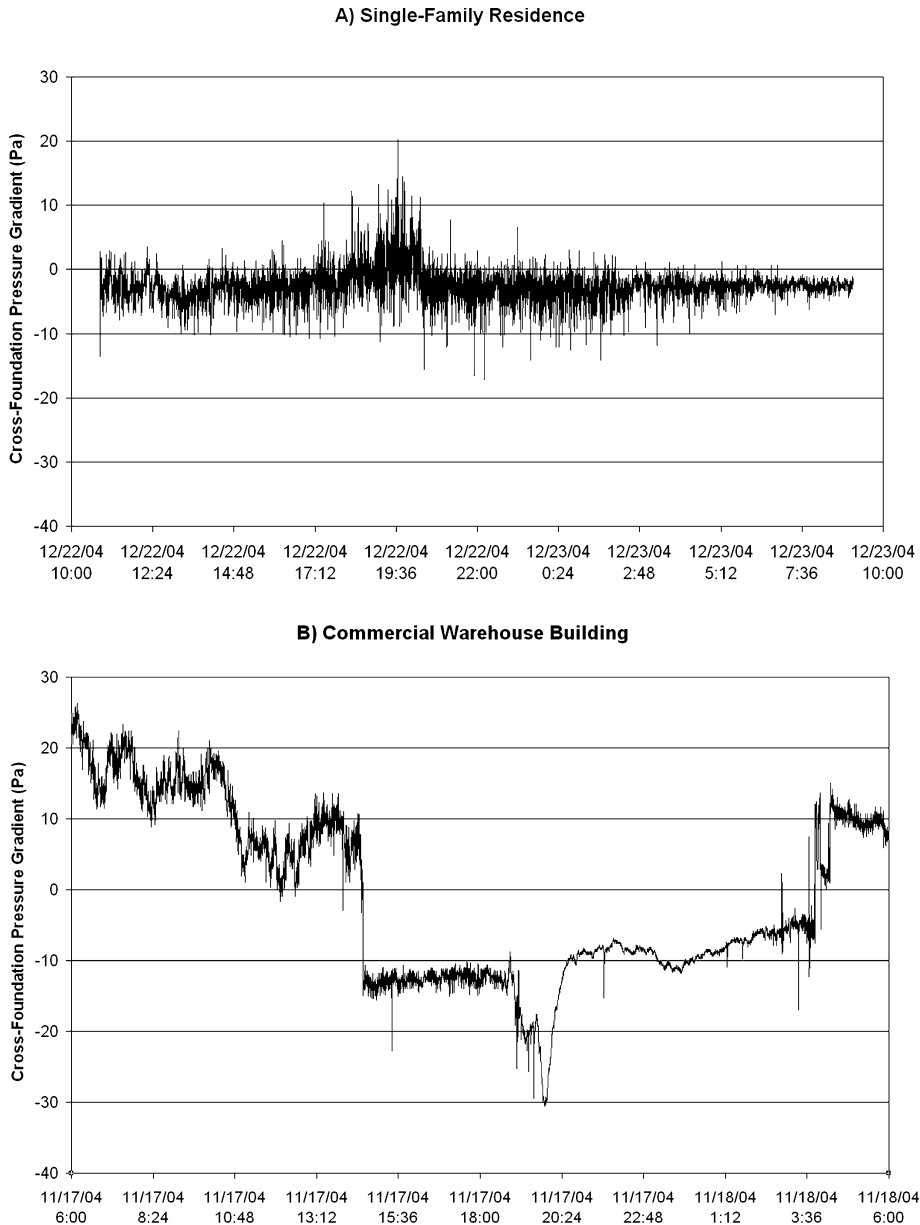


Figure 2. Measured cross-foundation pressure gradients: A) single-family residence, B) commercial warehouse building.

- The air is incompressible (a valid assumption for small pressure gradients).
- Adsorption and degradation of VOCs are negligible.
- Air in both the building and the sub-foundation soil is assumed to be perfectly and instantaneously mixed.

Advective rather than diffusive VOC transport was modeled because the limited literature available suggests that VOC exchange through the building foundation is commonly

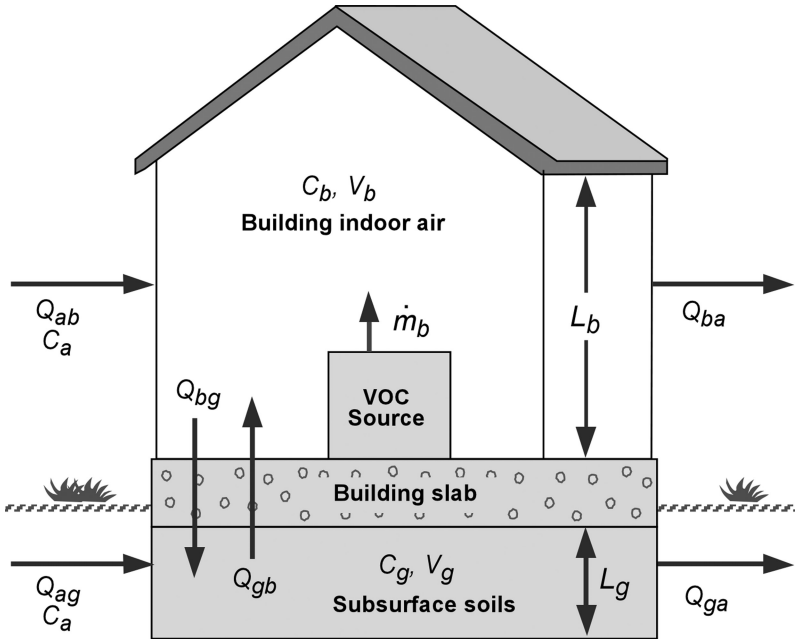


Figure 3. Advection model input parameters.

controlled by advective flow rather than diffusion (Nazaroff *et al.*, 1985, 1987). In addition, Johnson and Ettinger (1991) indicate that in a sandy soil, the ratio of advective to diffusive transport rates (expressed as a Peclet number) for typical pressure gradients of 1 to 10 Pa ranges from 10 to 100, indicating advection-dominated transport through the building foundation.

Adsorption has been neglected in the model because the typical slab-on-grade building is underlain by clean sand backfill that is very low in organic carbon content and, therefore, the adsorption capacity of this type of sand is expected to be very low. However, inclusion of equilibrium partitioning to account for adsorption to subsurface soils would simply have the effect of increasing the effective volume of the subsurface soil compartment in the model.

A volume balance results in the following relationship between the volumetric flow rates in the building and subsurface, respectively:

$$Q_{ab} + Q_{gb} = Q_{bg} + Q_{ba} \quad (1)$$

$$Q_{bg} + Q_{ag} = Q_{gb} + Q_{ga} \quad (2)$$

where:

Q_{ab} = Volumetric flow rate of air into the building from the ambient air ($L^3 T^{-1}$).

Q_{ba} = Volumetric flow rate of air out of the building into the ambient air ($L^3 T^{-1}$).

Q_{ga} = Volumetric flow rate of air from the subsurface below the foundation into the surrounding soil ($L^3 T^{-1}$).

Q_{ag} = Volumetric flow rate of air from the surrounding soil into the subsurface below the foundation ($L^3 T^{-1}$).

Q_{gb} = Volumetric flow rate of air from the soil underlying the foundation into the building ($L^3 T^{-1}$).

Q_{bg} = Volumetric flow rate of air from the building into the soil underlying the foundation ($L^3 T^{-1}$).

Under positive pressure conditions, air flows from the building to the subsurface soil, and Q_{gb} and Q_{ag} are 0. A mass balance on the building indoor air and subsurface soil yields a set of two ordinary differential equations:

Mass balance on building (positive pressure):

$$V_b \frac{dC_b}{dt} = Q_{ab}C_a - Q_{ba}C_b - Q_{bg}C_b + \dot{m}_b \quad (3)$$

Mass balance on subsurface soil (positive pressure):

$$V_g \frac{dC_g}{dt} = Q_{bg}C_b - Q_{ga}C_g \quad (4)$$

With initial conditions specified as:

$$C_{b,0} = 0 \quad \text{and} \quad C_{g,0} = 0 \quad \text{at} \quad t = t_0 \quad (5)$$

where:

V_b = Air volume of building (L^3).

V_g = Air volume of subsurface soil beneath foundation (L^3).

C_a = Concentration in ambient air and subsurface soil surrounding the building (but not beneath the foundation), usually assumed to be constant (ML^{-3}).

C_b = Concentration in building indoor air (ML^{-3}).

C_g = Concentration in subsurface soil beneath the foundation (ML^{-3}).

\dot{m}_b = Transient mass release rate of VOC from an indoor source (MT^{-1}).

The VOC mass release rate, \dot{m}_b , is a time-dependent variable that can be used to describe the transient release of VOCs from a variety of indoor sources. For example, a first-order decay function could be used for the release of VOCs from drying paint, or a step function could be used to describe the sublimation of a volatile solid (see ‘‘Simulation of Indoor VOC Sources’’ below).

Under negative pressure conditions, air flows from below the foundation into the building, and Q_{bg} and Q_{ga} are 0. A mass balance on the building indoor air and subsurface soil yields a similar set of equations:

Mass balance on building (negative pressure):

$$V_b \frac{dC_b}{dt} = Q_{ab}C_a - Q_{ba}C_b + Q_{gb}C_g + \dot{m}_b \quad (6)$$

Mass balance on subsurface soil (negative pressure):

$$V_g \frac{dC_g}{dt} = -Q_{gb}C_g + Q_{ag}C_a \quad (7)$$

Key model variables are illustrated in Figure 3. The foundation pore space is assumed to occupy a negligible volume relative to the building and sub-foundation soil, so that the concentration of VOCs within the foundation is assumed to be at a pseudo steady state. The concentration of VOCs within the cracks in the foundation is equal to the building concentration under positive pressure conditions and equal to the subsurface vapor concentration

under negative pressure conditions. The volumetric flow rate of air through the building foundation is calculated using the method of Johnson and Ettinger (1991):

$$Q_{bg}(\text{or } Q_{gb}) = \frac{2\pi \Delta P(t) k_v X_{\text{crack}}}{\mu_a \ln \left(\frac{2Z_{\text{crack}}}{r_{\text{crack}}} \right)} \quad (8)$$

where:

$\Delta P(t)$ = Time-dependent function representing the pressure difference between the building and the soil underlying the foundation ($\text{ML}^{-1} \text{T}^{-2}$).

k_v = Permeability of soil to air (L^2).

X_{crack} = Floor-wall seam perimeter (L).

μ_a = Air viscosity ($\text{ML}^{-1} \text{T}^{-1}$).

Z_{crack} = Crack depth below grade (L).

r_{crack} = Equivalent crack radius (L).

and

$$X_{\text{crack}} = 4\sqrt{A_s} \quad (9)$$

$$r_{\text{crack}} = \eta(A_s/X_{\text{crack}}) \quad (10)$$

where:

η = Ratio of foundation crack area to total foundation area.

A_s = Total foundation area (L^2).

Johnson (2002) and others have suggested that Equation 8 does not provide a reliable prediction of Q_{bg} and Q_{gb} . As discussed below, alternative methods for specifying Q_{bg} and Q_{gb} yield similar results.

The advection model consists of Equations 1, 2, 3, 4, 5, and 8 for positive pressure conditions and Equations 1, 2, 5, 6, 7, and 8 for negative pressure conditions. The system of equations is solved at each time step in a spreadsheet according to the following sequence:

- The value of $\Delta P(t)$ is calculated or specified according to the pressure difference function for the simulation.
- The value of \dot{m}_b is calculated or specified according to the mass release function for the simulation.
- Q_{bg} is calculated using Equation 8.
- The other volumetric flow rates are calculated from Equations 1 and 2.
- Equations 3 and 4 or 6 and 7 are then solved using a fourth-order Runge-Kutta method (Chapra and Canale, 2001).

The spreadsheet solution method yielded a working model that could be used to explore the impact of indoor VOC sources on below-foundation soil gas.

Model Input Parameter Values

In order to obtain model simulation results comparable to other commonly used vapor intrusion models, input parameters representative of a residential building were selected from US EPA guidance (US EPA, 2003). Ambient VOC concentrations were assumed to be zero at all times (i.e., $C_a = 0$) and initial indoor and below-foundation concentrations were assumed to be zero (i.e., $C_{b,0} = 0$ and $C_{g,0} = 0$ at $t = 0$).

To represent periodic pressure gradient reversals, the pressure gradient was varied sinusoidally according to the following function:

$$\Delta P(t) = \Delta P_{\max} \cos(2\pi t \nu_p) \quad (11)$$

where:

ΔP_{\max} = Maximum pressure gradient.

ν_p = Frequency of pressure cycles (T^{-1}).

t = Time(T).

A maximum pressure gradient (ΔP_{\max}) of 4 Pa was used. This pressure gradient is the US EPA (2003) default value. The pressure difference was assumed to vary with a frequency of 12 d^{-1} (i.e., the pressure difference varied from +4 Pa to -4 Pa then back to +4 Pa every 2 hours). The period of the fluctuations does not have a large effect on the simulation results. Shorter pressure fluctuation periods cause the concentration response curves to approach a smooth line, while longer pressure fluctuation periods cause greater short-term variation in VOC concentration, but do not change the long-term average concentrations. The mathematical function used to vary the pressure also has little effect on the results. Either a step function resulting in instantaneous switch from maximum positive pressure to maximum negative pressure or a random variation between the maximum positive and maximum negative pressures yields results similar to the sinusoidal pressure variation. Other model input parameters used for the model simulations are provided in Table 2.

Simulation of Indoor VOC Sources

To evaluate the impact of bi-directional VOC transport between indoor air and subsurface soils, the advection model was used to simulate indoor and below-foundation VOC concentrations over a 5-day period under two different source types: i) a transient indoor VOC source of constant mass release rate for 24 hours followed by no VOC release for the remainder of the simulation (constant source), and ii) a transient source with an exponentially decreasing mass release rate (first-order source). The constant source approximates the release of a volatile solid or liquid such as an indoor pesticide application. The first-order source represents the release of VOCs from sources where the VOC emission rate decreases as the product cures or ages (e.g., fresh paint or new carpet). In both scenarios, the VOC mass release rate was set to achieve a maximum indoor air concentration equal to approximately 100 ug/m^3 , well below the maximum indoor concentration of common VOCs reported in the literature (e.g., 1500 ug/m^3 for 1,4-dichlorobenzene and 2200 ug/m^3 for toluene; Samfield, 1992).

In the first scenario (constant-source), an indoor VOC mass release rate of 140 mg/day was assumed for the first 24 hours of the simulation, with no VOC release thereafter. The results of the simulation are shown in Figure 4. The indoor air VOC concentration reaches a value of approximately 100 ug/m^3 within one day, then starts to decrease when the source is removed. The below-foundation concentration increases to approximately 30 ug/m^3 , then also begins to decrease, but at a much slower rate because of the resistance to sub-foundation and indoor air exchange imposed by the building foundation. While the building VOC concentration can be detected for less than 2 days (assuming a detection limit of 0.5 ug/m^3), the below-foundation VOCs persist at detectable concentrations for nearly 5 days.

In the second scenario (first-order source), an initial indoor VOC mass release rate of 240 mg/day was specified, and the mass release rate decreased exponentially according to

Table 2
Advection model input parameters

Parameter	Symbol	Units	Value	Source of value *
Model parameters and constants				
Air exchange ratio	AER	hr^{-1}	0.25	1
Total building foundation area	A_s	m^2	100	1
Concentration of constituent in ambient air	C_a	ug/m^3	0	2
Permeability of soil to air	k_v	m^2	3×10^{-11}	1
Building ceiling height	L_b	m	2.44	1
Below-foundation soil thickness	L_g	m	0.3	2
Maximum building/subsurface soil pressure gradient	ΔP_{max}	Pa	4	1
Crack depth below grade	Z_{crack}	m	0.15	1
Soil porosity	ϕ	—	0.43	1
Ratio of foundation crack area to total foundation area	η	—	0.00038	1
Air viscosity	μ_a	$\text{kg}/\text{m}\cdot\text{d}$	1.56	1
Pressure reversal frequency	ν_p	d^{-1}	12	2
Calculated values				
Equivalent crack radius	r_{crack}	m	0.00095	Equation 10
Air volume of building	V_b	m^3	244	3
Air volume of subsurface soil beneath building	V_g	m^3	12.9	4
Floor-wall seam perimeter	X_{crack}	m	40	Equation 9

Notes:

¹US EPA Guide default value (US EPA, 2003).

²Assumed.

³ $V_b = L_b A_s$.

⁴ $V_g = L_g A_s \phi$.

the following expression:

$$\dot{m}_b = \dot{m}_{b,0} e^{-k_{\text{source}} t} \quad (12)$$

where:

$\dot{m}_{b,0}$ = Initial mass release rate of indoor source (MT^{-1}).

k_{source} = Source mass release rate first-order rate constant (T^{-1}).

The source decay constant was set at 2.3 d^{-1} , which results in a mass release rate decrease of approximately one order of magnitude per day. The maximum building concentration reaches a value of approximately $100 \text{ ug}/\text{m}^3$ at a time approximately 8 hours after the beginning of the simulated release while the subsurface concentration reaches a maximum concentration of $20 \text{ ug}/\text{m}^3$ after 20 hours (see Figure 4). As with the constant source scenario, the VOCs persist in the subsurface at detectable concentrations after decreasing below detection limits indoors.

In both model scenarios, VOCs originating in the building migrate to the sub-foundation at concentrations above typical analytical detection limits. In both cases, the relationship

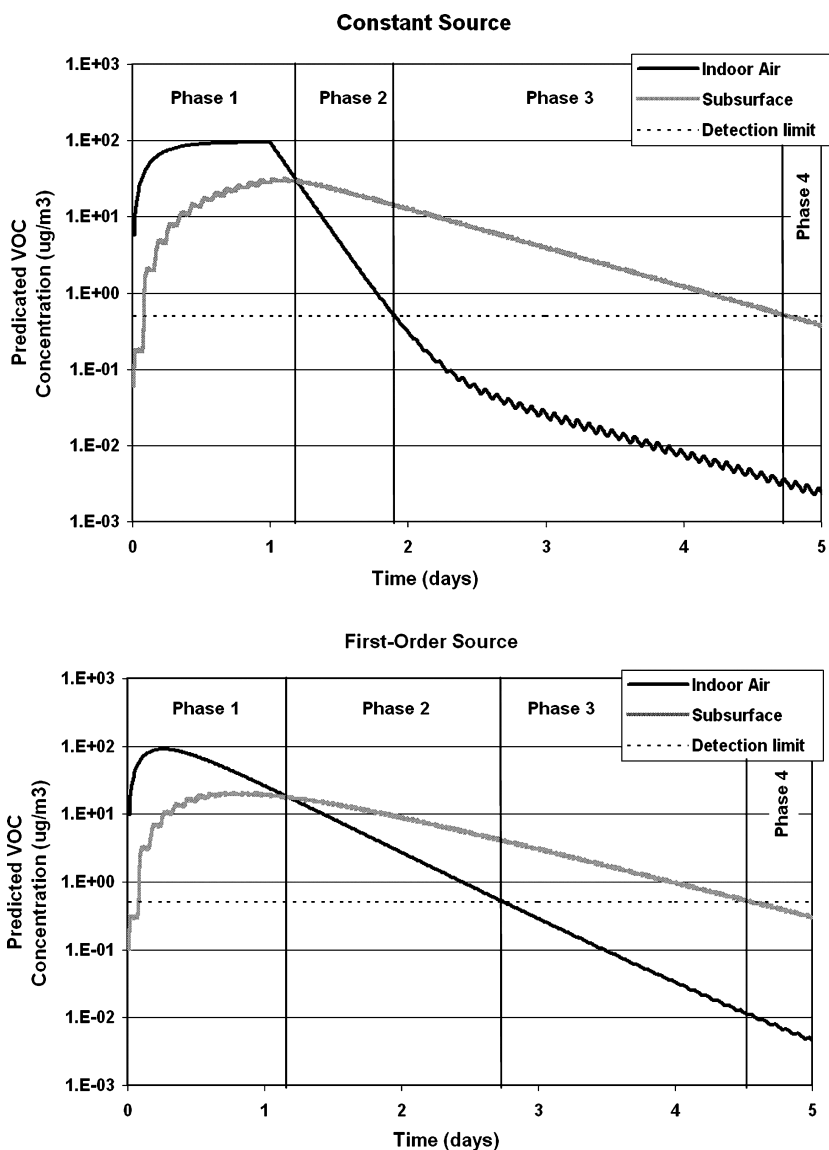


Figure 4. Predicted indoor and subsurface VOC concentrations following transient indoor VOC release. Detection limit represents typical detection limit for VOC analysis of bulk air samples. Phase 1—VOCs detectable in indoor air and subsurface with higher concentration in indoor air; Phase 2—VOCs detectable in indoor air and subsurface with higher concentration in subsurface; Phase 3—VOCs detectable in subsurface but not indoor air; Phase 4—VOCs not detectable in indoor air or subsurface.

between the indoor air VOC concentration and the below-foundation VOC concentration can be described in four phases: 1) VOCs detectable in both compartments with indoor air concentrations greater than below-foundation concentrations, 2) VOCs detectable in both compartments with indoor air concentrations less than below-foundation concentrations, 3) VOCs detectable below the foundation but not detectable in indoor air, and 4) VOCs not detectable in either compartment.

For the purpose of evaluating subsurface vapor intrusion, phases 2 and 3 are of particular concern. Sampling conducted during these two phases would indicate a VOC concentration gradient from below the foundation into the building even though the original VOC source was indoors. In both model scenarios, phases 2 and 3 cover more than 60% of the 5-day simulation period, indicating a significant potential for measuring a higher VOC concentration in the subsurface than in the building following the release of a transient indoor VOC source. These measurement results could easily be misinterpreted as an indication of subsurface VOC vapor intrusion.

Model Sensitivity Analysis

Two key sources of uncertainty in the model inputs are: i) the advective air flow rate through the building foundation under positive and negative building pressure conditions (Q_{bg} and Q_{gb}), and ii) the prevalence of positive versus negative building pressure conditions. In order to evaluate the applicability of the model results to a variety of building conditions, a sensitivity analysis was performed for these two model inputs.

The model input values used for the base model simulations yield values of Q_{bg} and Q_{gb} , which vary from 0 to 14 L/min over the range of building pressures specified. For comparison, Ettinger (2005) suggests that advective flow through the building foundation typically ranges between 1 and 10 L/min for single-family residences, while Johnson (2002) suggests that advective flow through the building foundation can be estimated as 0.0001 to 0.05 times Q_{ab} , corresponding to a range of 0.1 to 50 L/min for a typical single-family residence. In order to evaluate the effect of variations in Q_{bg} and Q_{gb} on the model results, the maximum pressure gradient (ΔP_{\max}) was varied to achieve maximum Q_{bg} and Q_{gb} values ranging from 0.5 to 50 L/min. For low advective flow rates, the maximum subsurface VOC concentration ($C_{g,\max}$) was lower than the base case, but the time period over which the VOC persisted below the building foundation above detectable concentrations was greater. For high advective flow rates, $C_{g,\max}$ was higher than the base case, but the time period over which the VOC persisted below the building foundation above detectable concentrations was lower. In all cases, there were periods of time during which subsurface VOC concentrations were higher than indoor VOC concentrations.

Although the base model scenarios assumed equal frequency of positive and negative building pressure conditions, the prevalence of positive versus negative building pressures will vary from building to building. To evaluate the impact of predominately positive or negative building pressures on the model results, building pressure was varied from +4 Pa to -4 Pa in a step-wise fashion rather than the sinusoidal variation of the base case. The prevalence of positive pressure conditions was varied from 5% to 95%. In other words, positive pressure conditions were simulated for a period of 6 minutes out of every 2 hours to 114 minutes out of every 2 hours. As the prevalence of positive pressure conditions increases, both the maximum subsurface VOC concentration ($C_{g,\max}$) and the percentage of the simulation time for which the subsurface VOC concentration is greater than the indoor VOC concentration increases. $C_{g,\max}$ is directly proportional to the prevalence of positive pressure conditions, so for a positive pressure prevalence of 75%, $C_{g,\max}$ is 50% higher than the base case and for a positive pressure prevalence of 25%, $C_{g,\max}$ is 50% lower than the base case. The sensitivity analysis also indicated that transient indoor VOC sources can result in subsurface VOC concentrations that are higher than indoor VOC concentrations under a wide variety of pressure scenarios. When positive building pressure conditions occurred less than 15% of the time, subsurface VOC concentrations were never higher than indoor VOC concentrations. However, when

positive pressure conditions occurred more than 30% of the time, subsurface VOC concentrations exceeded indoor VOC concentrations for at least 50% of the 5-day simulation period.

In addition to the pressure assumptions described above, other model input parameters can significantly affect the results. A lower below-foundation soil permeability greatly increases the persistence of VOCs in the subsurface following removal of the indoor VOC source. For example, a soil permeability representative of a fine-grained sand (i.e., 1×10^{-12} m²) results in the presence of detectable VOC concentrations in the subsurface for more than 30 days following the release of a transient indoor VOC source. In contrast, although not considered in the model, wind-driven advection of outdoor air through the below-foundation soils (Fischer *et al.*, 1996) could serve to reduce the magnitude and duration of subsurface VOC impacts from indoor sources.

The sensitivity analysis indicates that the advection model presented here provides qualitatively similar results over a broad range of building pressure conditions. However, the quantitative model results vary significantly depending on the selection of model input parameters. As a result, the model should be considered a qualitative tool for the evaluation of potential VOC exchange between a building interior and the subsurface. Indoor VOC sources of higher mass flux or longer duration result in higher below-foundation VOC concentrations. The specific model results presented for the base case scenarios are intended to illustrate the types of VOC concentration gradients that may be observed between indoor air and subsurface vapors following the release of a transient indoor VOC source. The results are not intended to quantify the magnitude or duration of these relationships in specific buildings.

Field Evaluation of Below-Foundation VOC Impacts

Independent of model simulations, field measurements of indoor and below-foundation VOC concentrations have also indicated the migration of VOCs from indoor air into the subsurface. Indoor air and below-foundation samples collected from three apartments at a complex in Fort Worth, Texas, show that VOCs originating indoors have migrated into the subsurface and are present at detectable concentrations. Although this is a limited data set from a single site, the results provide a preliminary indication that VOC transport from indoor to the subsurface can occur.

Sample Collection and Analysis

An indoor air and below-foundation vapor sampling program was conducted in three vacant apartments within an apartment complex in Fort Worth, Texas. The initial purpose of the sampling program was to evaluate the potential for vapor intrusion impacts associated with methyl-tertiary butyl ether (MTBE) detected in a groundwater monitoring well upgradient of the property at an adjacent former gas station. Groundwater samples from the adjacent property have been analyzed for benzene (16 to 4,800 ug/L), ethylbenzene (3 to 490 ug/L), toluene (<5 to 11 ug/L), xylenes (<5 to 1,000 ug/L), and MTBE (2,450 to 14,000 ug/L). MTBE was the primary contaminant detected in the downgradient well located between the gas station and the apartment complex and was present in this well at a concentration of 6,500 ug/L.

The sampling program involved the collection and laboratory analysis of indoor and outdoor air samples and below-foundation vapor samples across the apartment complex. Below-foundation soil vapor and indoor air sampling was conducted at three vacant ground-floor

apartment units. Sampling locations were positioned away from visible cracks in the slab to maximize the collection of soil vapors held beneath the slabs. Within each sampled apartment unit, the slab was cored at two locations. The first hole was used for geotechnical sampling and the second hole was used for the actual soil vapor sampling. During the coring procedure, the volume of fresh water used to lubricate the core barrel was minimized in order to avoid inhibition of vapor flow from the introduction of water into the sub-foundation layer. A wet vacuum was used to remove lubricating water throughout the coring process.

Within each sampled apartment unit, an initial 4-inch diameter hole was cored to: 1) determine the slab thickness, 2) determine the presence and thickness of a backfilled sub-slab layer, and 3) collect a sample from the sub-slab layer for field classification. Samples were collected with a hand auger and visually logged by the on-site geologist. Field observations indicated that the sub-slab sand bed was present beneath each of the three sampled apartment units. Apparent moisture content of the sub-slab sand bed across the site ranged from none to slightly moist.

Foundation penetrations used for geotechnical sampling were patched following completion of the geotechnical sampling to prevent the possible exchange of indoor air and subsurface soil vapors through the slab. Clean sand (i.e., filter pack sand commonly used in monitoring well installations) was placed within the cored hole and compacted by hand. A thin layer of hydrated powdered bentonite (approximately 1-inch thick) was placed atop the sand at the base of the slab to function as a seal. The remaining void space through the slab was filled with concrete and finished flush with the surrounding slab surface.

One day after collection of the geotechnical samples, below-foundation soil vapor samples were collected through a 1.25-inch diameter hole cored within 2 feet of each geotechnical sampling location. To prevent water used during the coring process from entering the sub-foundation layer, coring was stopped approximately 0.25 inches above the base of the slab. Water within the partial slab penetration was removed with a wet vacuum before the remainder of the hole was drilled with a rotary impact drill that does not require the use of water. Below-foundation soil vapor samples were collected from the approximate mid-point of the sand bed using perforated Teflon[®] tubing connected to dedicated 6-liter Summa canisters. Immediately prior to sample collection, the sampling train was purged with a separate Summa canister to remove air present within the system, since this air would not be representative of actual subsurface vapor conditions. The purged volume equaled one to two times the calculated volume of air contained within the tubing and the slab penetration.

Below-foundation vapor samples were collected continuously over a 2-hour period at an approximate flow rate of 0.05 liters per minute to minimize vacuum effects created during the sampling process. An outdoor ambient air sample was collected adjacent to the former gas station property. An indoor air sample was collected within each of the three sampled apartment units. Both the indoor air and outdoor ambient air samples were collected directly into dedicated 6-liter Summa canisters over a 2-hour period at an approximate flow rate of 0.05 liters per minute concurrent with the below-foundation vapor sampling. All samples were analyzed for VOCs at a commercial laboratory by US EPA Method TO-14A.

Sample Results and Discussion

One or more VOCs were detected in five of the seven samples collected from the site. No VOCs were detected in the one outdoor ambient air sample; however, VOCs were detected in two of three indoor air samples and in three of three below-foundation samples. A total

Table 3
VOC analyses of air and vapor samples at a Texas apartment complex (ug/m³)

Chemical	Apt. 113		Apt. 123		Apt. 163		Outdoor air
	IA	SS	IA	SS	IA	SS	
Dichlorobenzene, 1,4-	35	62	<1	<1	76	12	<1
Methylene Chloride	21	<1	<1	20	83	<1	<1
Toluene	5	5	<1	6	4 J	4	<1
Xylene, o-	4 J	<1	<1	<1	<1	<1	<1

Notes:

¹Samples analyzed for 43 VOCs by US EPA Method TO-14A. Table shows VOCs detected in one or more sample.

²J = Estimated concentration below laboratory quantitation limit.

³IA = Indoor air, SS = Sub-slab.

⁴< = Compound analyzed but not detected at the detection limit shown.

of 4 out of 43 VOCs on the Method TO-14A analyte list were detected in one or more samples: 1,4-dichlorobenzene (detected in four samples), methylene chloride (detected in three samples), toluene (detected in five samples), and o-xylene (detected in one sample). Sample results are summarized on Table 3.

Although the original goal of the sampling program was to determine whether VOCs from the adjacent former gas station site were causing a vapor intrusion impact, the results indicate that the detected VOCs likely originated from indoor air sources. All four of the detected VOCs (1,4-dichlorobenzene, methylene chloride, toluene, and o-xylene) are commonly found in indoor air at sites without soil or groundwater contamination (McHugh et al., 2003). Many potential sources of these VOCs have been identified in the literature including the specific common household sources discussed below. The similarity in analytes detected in the three apartment units likely indicates that the sources of these VOCs are common to the three units. 1,4-dichlorobenzene is commonly used as an insecticide for the control of moths and carpet beetles and as a toilet bowl deodorizer. It is estimated that 35% to 55% of 1,4-dichlorobenzene manufactured is used for moth control. At the time of the sampling, the apartment complex did have a routine program of pesticide application in the apartment units for control of indoor pests. Consumer products containing methylene chloride, toluene, and o-xylene include paint strippers, solvents, aerosols, adhesives, paints, and glues. Although both toluene and o-xylene are constituents of gasoline, neither of these constituents were detected in the groundwater monitoring well located directly upgradient of the apartment property. As a result, it is unlikely that these constituents would have migrated from the former gas station site in the absence of MTBE, which was present upgradient of the apartment complex at a concentration of 6,500 ug/L. In addition, the maximum concentrations of benzene (4,800 ug/L) detected in groundwater from the gas station was higher than the maximum concentration of either toluene (11 ug/L) or xylenes (1,000 ug/L) indicating that benzene would be more likely than toluene or xylenes to migrate from the gas station to the apartment complex. In contrast, the vacant apartments sampled were being painted or had recently been painted in preparation for rental, providing a potential indoor source of both toluene and o-xylene. Therefore, indoor sources are the most likely explanation for the presence of the four detected VOCs in both indoor air and below-foundation vapor samples.

As shown on Table 3, concentrations of methylene chloride and toluene in Apt. 123 and 1,4-dichlorobenzene in Apt. 113 were higher in below-foundation samples than in indoor samples, indicating that the migration of VOCs from indoor air to below-foundation soil vapors occurred prior to penetration of the foundation for the sample collection. These results are consistent with the model simulations indicating that elevated concentrations of VOCs can persist in the subsurface following a transient indoor release even after the VOCs have dissipated from indoor air. Because the original goal of the sampling program was to determine the presence or absence of a subsurface vapor intrusion impact at the apartment complex, no additional sampling was conducted to further evaluate the transport of VOCs from indoors to the below-foundation soils.

Discussion and Recommendation

The model simulations and field data presented above support the conclusion that indoor air sources of VOCs can impact the below-foundation soil gas, complicating the field evaluation of vapor intrusion at corrective action sites. A simple advection model has been developed that allows for both positive and negative building pressures relative to below the foundation. The model provides for the simulation of reversible air exchange between the indoor air and the sub-foundation soil gas allowing an evaluation of the impact of indoor VOC sources on below-foundation soil gas. This model indicates that transient indoor VOC sources can result in significant concentrations of VOCs below the building foundation. Transient simulations of a constant source and a first-order source yielded below-foundation concentrations of 30% and 20% of the peak indoor air concentrations, respectively. As a result, a building that had recently experienced a peak benzene concentration resulting from a transient indoor source equal to the 90% percentile indoor air benzene concentration (15.3 ug/m^3 ; Sexton *et al.*, 2004) could also have a below-foundation benzene concentration of 4.6 ug/m^3 , greater than the US EPA benzene screening value for below-foundation samples (3.1 ug/m^3 ; US EPA, 2002). The model simulations further indicate that the below-foundation benzene could persist at concentrations above the US EPA screening values even after the indoor air concentration falls below the analytical detection limit (0.5 ug/m^3). As a result, application of the US EPA screening values to below-foundation sample results could erroneously indicate a potential for subsurface vapor intrusion impacts even at sites where indoor releases represent the only source of VOCs at the site.

Field data collected from an apartment complex in Texas confirm model predictions that indoor VOCs can impact the below-foundation soil gas. Four VOCs commonly associated with indoor sources (1,4-dichlorobenzene, methylene chloride, toluene, and xylene) were detected in indoor and below-foundation samples collected from three vacant apartments. Indoor sources were identified as the most likely source of these VOCs at this site. In two of three apartments sampled, the below-foundation VOC concentration was higher than the indoor VOC concentration, confirming that VOCs originating from indoors can persist in the subsurface after dissipating from indoor air. These results indicate that indoor sources can result in a misleading concentration gradient between below-foundation samples and indoor samples, with below-foundation VOC concentrations exceeding indoor concentrations in some cases. These findings should be used to update the conceptual model for vapor intrusion in order to account for bi-directional vapor exchange across building foundations.

Based on the finding that bi-directional transport of VOCs can occur between indoor air and the subsurface, the conceptual model of vapor intrusion and associated regulatory guidance should include the following considerations:

- The use of a wide variety of volatile chemicals indoors commonly results in indoor VOC concentrations above US EPA screening guidance levels (see Table 1). Transient indoor sources can result in peak indoor VOC concentrations far higher than these levels.
- Some buildings are expected to experience both positive and negative building pressures relative to the subsurface within a typical 24-hour period. This pressure fluctuation can result in bi-directional exchange of air across the building foundation, creating a mechanism for VOCs that originate indoors to migrate into the subsurface. In addition, some buildings may typically operate under positive pressure conditions (Bearg, 1993), resulting in continuous transport of indoor air through the building foundation.
- VOCs originating from indoor sources can persist in the subsurface longer than they persist in indoor air. This persistence can result in subsurface VOC concentrations greater than those detected in indoor air even in situations where the indoor air is the only source of the VOCs.

Although indoor and below-foundation VOC measurements represent one line of evidence for the evaluation of potential vapor intrusion impacts, ignoring the potential for bi-directional transport of VOCs through the building foundation can result in a misinterpretation of indoor and subsurface VOC sampling results, with concomitant incorrect conclusions regarding the presence or absence of vapor intrusion impacts at buildings located in the vicinity of subsurface VOC contamination. Although the detection of VOCs directly below a building foundation may indicate the migration of VOCs from subsurface soils, these results may also indicate the migration of VOCs from indoor sources. Therefore, an accurate understanding of pressure and VOC concentration gradients around the building is required in order to properly interpret the VOC concentration results.

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