Journal of the Air & Waste Management Association

ISSN: 1047-3289 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/uawm20

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To cite this article: Ian Hers , Reidar Zapf-Gilje , Loretta Li & Jim Atwater (2001) The Use of Indoor Air Measurements To Evaluate Intrusion of Subsurface VOC Vapors into Buildings, Journal of the Air & Waste Management Association, 51:9, 1318-1331, DOI: 10.1080/10473289.2001.10464356

To link to this article: http://dx.doi.org/10.1080/10473289.2001.10464356

Published online: 27 Dec 2011.

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TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **51**:1318-1331
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The Use of Indoor Air Measurements To Evaluate Intrusion of Subsurface VOC Vapors into Buildings

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ABSTRACT

The implementation of a risk-based corrective action approach often requires consideration of soil vapor migration into buildings and potential inhalation exposure and risk to human health. Due to the uncertainty associated with models for this pathway, there may be a desire to analyze indoor air samples to validate model predictions, and this approach is followed on a somewhat frequent basis at sites where risks are considered potentially significant. Indoor air testing can be problematic for a number of reasons. Soil vapor intrusion into buildings is complex, highly dependent on site-specific conditions, and may vary over time, complicating the interpretation of indoor air measurements when the goal is to deduce the subsurface-derived component. An extensive survey of indoor air quality data sets highlights the variability in indoor volatile organic compound (VOC) concentrations and numerous sources that can lead to elevated VOC levels. The contribution from soil vapor is likely to be small relative to VOCs from other sources for most sites. In light of these challenges, we discuss how studies that use indoor air testing to assess subsurface risks could be improved. To provide added perspective, we conclude by comparing indoor air concentrations and risks arising from subsurface VOCs, predicted using standard model equations for soil vapor fate and intrusion into buildings, to those associated with indoor sources.

IMPLICATIONS

The key implication of this paper is that the use of indoor air concentrations to deduce the subsurface-derived vapor component is not straightforward, and that an integrated approach that recognizes the factors that affect soil vapor intrusion and indoor air quality is needed. Since there are several other significant sources of VOCs besides soil vapor, distinguishing the vapor component from other sources will, in practice, be difficult. Model predictions suggest that the soil vapor-derived exposure and risk could range from being much less than to much greater than the risk associated with other VOC sources. Further development of protocols for indoor air sampling and validation of predictive models for soil vapor intrusion are needed to improve risk assessments for this exposure pathway.

INTRODUCTION

The implementation of risk-based corrective action at contaminated sites is now commonplace. Soil vapor intrusion into buildings is a potential exposure pathway at many sites impacted by subsurface volatile organic compounds (VOCs), and this pathway is included in many regulatory standards and guidance documents pertaining to risk-based cleanup.[1,2] There is significant uncertainty associated with mechanisms for intrusion of VOCs into buildings and, consequently, with models used for this exposure pathway. In the face of this uncertainty, there may be a desire to analyze indoor air samples to validate model predictions, and this approach is followed on a somewhat frequent basis at sites where risks are considered to be potentially significant.[3,4] Indoor air testing can be problematic in terms of sampling methodology and data interpretation, since typically, there will also be indoor and outdoor sources of the VOC under consideration. In addition, the generation and fate of VOCs in indoor air are highly variable and building-specific.[5,6] While numerous studies on indoor air VOCs have been conducted, there is little information or guidance on the use of indoor air sampling to evaluate subsurface contamination VOC sources, or evaluation of the relative significance of subsurface versus indoor or outdoor air VOC sources.

The purpose of this paper is to provide an integrated overview on soil vapor intrusion and VOCs in buildings,

and to contribute to an improved understanding of critical mechanisms affecting VOC concentrations in buildings and appropriate sampling strategies. Mechanisms for soil vapor intrusion are initially evaluated, because this context is important in the design and interpretation of indoor air testing programs. Next, we provide an overview of the factors that contribute to indoor air quality, and compile measured VOC concentrations in indoor air from a number of sources. Possible improvements to indoor air sampling used to characterize subsurface sources are discussed, and essential complimentary measurements are identified. To provide added perspective on the relative importance of subsurface versus indoor air VOC sources, we conclude by comparing indoor air concentrations and risks arising from subsurface VOCs, predicted using standard equations for soil vapor fate and intrusion into buildings, to those associated with indoor sources. The focus of this paper is assessment of residential buildings.

MECHANISMS FOR SOIL VAPOR INTRUSION

Process Overview

Two compartments are defined to enhance our conceptual understanding of processes: the far-field, consisting of vadose zone soil, and the near-field, consisting of the subsurface building envelope (foundation) and nearby soil (Figure 1). If the depth to the contamination source below the building is significant, vadose zone processes such as diffusion, sorption, and biodegradation [for benzene, toluene, ethylbenzene, and xylenes (BTEX) and petroleum vapors] will likely have the greatest influence on VOC mass flux into a building. In this case, the VOC mass flux will be controlled by far-field processes, potentially resulting in nonsignificant concentrations below the building. Of greater concern for the soil vapor intrusion pathway are sites with relatively shallow VOC contamination, where it appears that VOC mass flux through pressure-driven advective transport of soil gas into buildings can be significant.[3] In this case, intrusion would be controlled by near-field processes. Several radon studies also suggest that radon intrusion by advection is typically a more significant process than is diffusion.[7-10] The most significant factors affecting the near-field compartment would therefore tend to be building underpressurization, the permeability of the building envelope and nearby soil, and depth to contamination.

Advective soil gas transport can occur through untrapped drains, perimeter cracks at the building wall and floor slab interface, service penetrations, expansion joints, and other cracks, if present. Driving forces for advection are pressure gradients caused by building underpressurization, changes in barometric pressure, and diurnal fluctuations in temperature.[11] The subsurface pressure and soil gas flow regime adjacent to and through the building envelope will be highly site specific and dependent on building construction, soil permeability, and potential preferential pathways, such as utility corridors. Building construction factors that may be significant include the presence of a basement, crawlspace, or water-vapor barrier, and the type of concrete (poured cement or cement block).

Positive soil-to-building pressure gradients can potentially have a significant effect on soil gas intrusion, as illustrated by several examples that follow. A study evaluating radon entry into a house near Chicago, IL, found higher building underpressurizations and radon entry rates during winter compared with summer months, and an advective radon flux that was greater than the

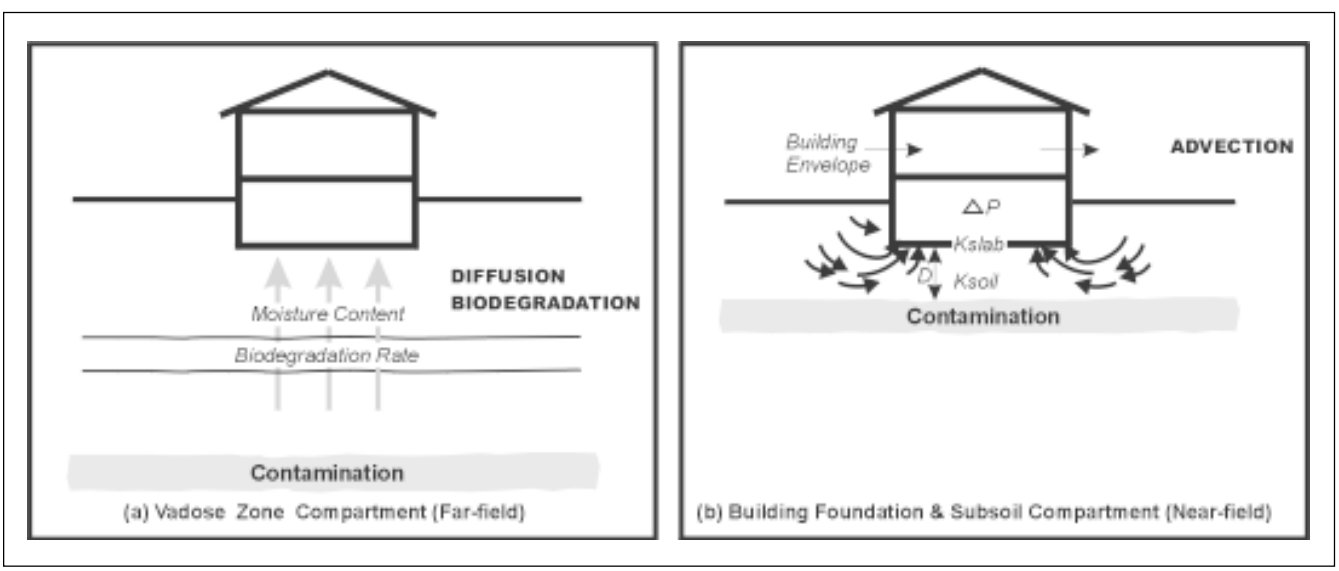

Figure 1. Possible conceptual model for soil vapor intrusion into buildings.

diffusive flux.[7] Another study found that average indoor radon levels were 12 times higher during winter compared with summer for 14 houses constructed on permeable soils in Spokane, WA.[12] The inferred reason for the difference was building underpressurization caused by the stack effect. A study of methane and VOC intrusion into a townhouse complex in Kitchener, Ontario, Canada, indicated that large short-duration cross-foundation pressure differences (up to 500 Pa) developed when barometric pressure decreased rapidly, and when the sub-slab foundation layer was not well vented to atmosphere (i.e., confined by low permeability material).[11] Consistently higher indoor VOC and methane concentrations were measured in townhouses during positive pressure gradients for two cycles of measurements (one cycle is a negative and positive pressure gradient). Another study compared the effect of atmospheric pressure fluctuations and sustained depressurization on advective radon entry into an experimental basement, and found that for sustained indoor-outdoor pressure differences greater than 1.5 Pa, atmospheric pressure fluctuations had essentially no effect on the time-averaged radon entry rate (i.e., sustained depressurization was much more important).[10] While it appears that short-term variation in atmospheric pressure can cause advective soil gas flow into a building, the most important determinant is whether there are conditions for sustained building depressurization arising from the stack effect, unbalanced mechanical ventilation systems, or possibly wind loading.[7,10,12-14]

Building Underpressurization and Ventilation

Building underpressurization is considered in greater detail because it can be the most significant driving force for VOC intrusion at sites with shallow contamination. Building ventilation rates are important because they can affect background indoor VOC concentrations.[15,16] Background concentrations are defined in this paper as not being related to soil vapor. In addition, both parameters are required when estimating model-predicted indoor VOC concentrations associated with soil vapor intrusion. Ventilation and building underpressurization are often linked in that forces that cause building underpressurization (e.g., stack effect arising from temperature differences) can result in ventilation, and conversely, unbalanced mechanical ventilation systems, or forced-air heating systems with leaking ducts, can cause buildings to be underpressurized.[17] It is noted that ventilation systems for commercial buildings in Canada and the United States are often designed to produce positive pressures in buildings relative to outdoor air, thereby reducing the potential for significant soil vapor intrusion.[13]

Building underpressurization is controlled by a combination of wind-loading, temperature differences between indoor and outdoor air (i.e., stack effect), forced-air mechanical ventilation systems, operation of furnaces and fireplaces, and appliance fans. Measured mean indoor-outdoor pressure differences for houses with basements, during the heating season, typically range from 2 to 10 Pa,[7,13,14,18,19] although this pressure difference can be as high as 15 Pa[18] (Table 1). The climatic conditions required for the higher pressure differences are severe winter conditions in Canada.[18] While there is little data specifically for slab-on-grade structures, two studies[14,20] suggest that a building underpressurization between 2 and 4 Pa may be reasonable for such structures. One researcher[18] has proposed a relatively comprehensive set of underpressurization values for various building types (Table 1). While simple empirical relationships can be used to estimate building underpressurization caused by wind-loading and temperature differences between indoor and outdoor air,[13] such estimates may be unreliable because of the complex mechanisms for building underpressurization.

Ventilation has three components consisting of (1) infiltration, or uncontrolled leakage of air into a building through openings in the building envelope; (2) natural ventilation through open windows and doors; and (3) mechanical ventilation provided by fans.[13] Ventilation rates reported in the literature vary significantly (Table 2). Two broad trends suggested by the data are a general reduction in ventilation rates over the past two decades, and lower ventilation rates for houses in cold climates (e.g., compare U.S. and Canadian data). In regions with relatively cold climates, the recent trend has been to construct "air-tight" houses with reduced ventilation rates to minimize energy consumption and costs (e.g., "R-2000" houses in Canada[16]). For houses with high energy efficient systems and those that typically have mechanical ventilation supplied through a heat recovery ventilator, ventilation rates may be as little as 0.1 air exchange per hour (ACH).[21] Reported ventilation rates also vary seasonally. In some cases, winter ventilation rates can exceed those measured in the summer, because pressure gradients caused by differences in indoor and outdoor temperature result in higher ventilation rates.[17] Summer ventilation rates will typically depend largely on natural ventilation and, hence, occupant use patterns.[22,23]

Standards in Canada and the United States both specify minimum ventilation rates for residential dwellings. In Canada, the CSA F326 standard for a three-bedroom house with unfinished basement is an outside air exchange of 70 L/sec, or ~0.5 ACH for a 100-m^2 bungalow with 100-m^2 basement.[17] In the United States, the ASHRAE 62-89 standard recommends an outside air ventilation rate of not less than 7.5 L/sec per person, and also not less than 0.35 ACH. It appears that mechanical ventilation systems

Table 1. Survey of building depressurization relative to atmospheric pressure.

Ref.	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Depressurization (Pa)	Comments
19[a]	Measured	Netherlands	Houses	N/A		~2	Between indoor space and crawlspace
			with crawlspace			~2	Between crawlspace and soil
14	Measured	Canada	Houses: Halifax (12), Ottawa/Hull (16), Winnipeg (12), Vancouver (12)	Winter 1993	Range	–5 to 15	Mix older and newer houses, most houses had forced air heating system and basement, depressurization correlated to house construction (full, partial basement, slab on grade) and climate
					Average for house	0.5 to 8.5	
9	Measured	Spokane River Valley, WA	House (14)	Winter	Average	2 to 6	
7	Measured	Chicago, IL	House (1)	Feb 17 to June 1, 1982	Range	0.6 to 4.3	Basement ΔP decreased between February and June 1
20	Predicted	Alameda, CA	Small commercial building (1)	N/A	Range	1 to 4	Predicted based on wind loading
8	Predicted	Portland, OR	2-story house	N/A		~2	Predicted based on wind loading and stack effect
			with basement			~2	
47	General reference	N/A	Houses	N/A		up to 10	Upper range associated with extreme weather conditions
18	Guidance	Canada	Slab-on-grade house	N/A	Range	1 to 3	Range mild to severe winter, without chimney
			Slab-on-grade house		Range	3 to 5	Range mild to severe winter, with chimney
			1- to 2-story house		Range	4 to 6	Range mild to severe winter, without chimney
			1- to 2-story house		Range	8 to 10	Range mild to severe winter, with chimney
			3-story house		Range	7 to 9	Range mild to severe winter, without chimney
			3-story house		Range	13 to 15	Range mild to severe winter, with chimney

Note: [a]References Put and Meijer, 1989 (report in Dutch); If the house has a fresh-air intake duct or combustion air supply, reduce differential pressures by 2 Pa. If the house has a fireplace, central exhaust system, or other large or frequently used exhaust equipment, increase the differential pressures by 2 Pa.

are quite frequently operated at less than the design or installed capacity.[16-18]

While we are not aware of studies involving detailed evaluation of the interaction between ventilation rate and building depressurization, we would intuitively expect the air exchange rate to increase as the building depressurization, due to stack effect, increased. In contrast, if the mechanical ventilation rate were to be decreased, we would expect the building depressurization, due to possible unbalanced flows, to also decrease, all other factors being equal. For these reasons, we suggest that it would be overly conservative to select very high building underpressurizations together with very low ventilation rates when using models to predict indoor air quality from subsurface VOC contamination.

INDOOR AIR QUALITY

Indoor VOC concentrations are affected by numerous factors, including indoor, outdoor, and potentially subsurface sources, air exchange between the building and outdoors, air movement within the building, interactions between the VOC and indoor sources, and chemical reactions.[5] Human activity and environmental factors, such as temperature and relative humidity, can also affect VOC levels. Elevated VOC concentrations in indoor air have been associated with adverse health effects, such as sensatory irritation and a broad-ranging and complex set of symptoms known as sick building syndrome (SBS).[24]

There are numerous indoor sources of VOCs, including building and construction products, furniture, carpets, textiles, household cleaners, sealants, glues, adhesives, paints, waxes, lubricants, heating systems (i.e., fuels), cooking vapors, human bioeffluents, personal care products, molds, and fungi.[25] Specific sources of indoor VOCs that are also common subsurface contaminants are listed in Table 3. The VOC emission rate varies widely depending on the material and time, and numerous studies have involved the use of small-scale environmental test chambers to evaluate emission rates.[26,27] Data from chamber tests are often fitted to empirical models, such as first-order decay models, to provide a means to predict indoor air quality. More sophisticated models for mass transfer, such as gas-phase-limited mass transfer, or within-material diffusion-limited emissions, have also been proposed.[28,29] In a few

Table 2. Survey of building ventilation rates.

Ref.	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
33	Measured PFT	Greater Toronto, ON, Canada	Houses (44)	Feb 12–April 9, 1996	Average	0.45	
					Median	0.4	
48	Measured PFT	U.S. Region 1	Houses (467)	All seasons	Mean	0.4	5th and 95th percentile = 0.1, 0.95
		U.S. Region 2	Houses (1496)	All seasons	Mean	0.55	5th and 95th percentile = 0.14, 1.38
		U.S. Region 3	Houses (332)	All seasons	Mean	0.55	5th and 95th percentile = 0.15, 1.25
		U.S. Region 4	Houses (1549)	All seasons	Mean	0.98	5th and 95th percentile = 0.21, 2.82
		U.S. Region 1	Houses (161)	Winter	Mean	0.36	5th and 95th percentile = 0.08, 0.90
		U.S. Region 1	Houses (254)	Spring	Mean	0.44	5th and 95th percentile = 0.14, 1.06
		U.S. Region 1	Houses (5)	Summer	Mean	0.82	5th and 95th percentile = 0.27, 2.01
		U.S. Region 1	Houses (47)	Fall	Mean	0.25	5th and 95th percentile = 0.1, 0.58
17	Measured PFT	Saskatoon, SK, Canada	Houses (20)	1993–1994 (9 months)	Minimum	0.08	All houses had natural gas forced-air heating systems and chimneys connected to the natural gas furnaces
					Average	0.2	
					Maximum	0.43	
15	Measured PFT	Canada	Houses (24)	1992–1993	Average	0.34	Most measurements in fall and winter months
25	Measured PFT	Saskatoon, Regina, SK; Tillsonburg, ON, Canada	Houses (44)	Jan 14–Feb 11, 1991	Average	0.34	
					Median	0.31	
34	Measured N_2O	Switzerland	Houses (10)	N/A	10th percentile	0.06	New houses or renovated houses
					50th percentile	0.16	
					90th percentile	2.06	
49	Measured PFT	USA	Houses (4000)	Mostly 1980s, early 1990s	Average	2	All regions (std. dev. = 3.3)
					Average	3.3	Southwest
					Average	0.6	Northeast
					Average	0.4	Northwest
					Average	0.5	Winter, all regions
					Average	1.9	Spring, all regions
					Average	5.4	Summer, all regions
					Average	0.4	Fall, all regions
50	Measured SF_6	Boise, ID	Houses (10)	Nov 15, 1986–Feb 4, 1987	Average	0.45	
					Median	0.45	
51	Measured PFT and HFB	Berlin, Germany	Houses (10)	Sept 1986–April 1987	Average	1.01	Older houses had statistically significant higher ACH (1.2) than did newer houses (0.88)
					Median	1.02	
52	Measured	USA	Houses	N/A	Typical range	0.5–1.5	Typical houses
						0.5–0.8	New or energy efficient houses, some as low as 0.2
23	Measured	ON, Canada	Houses (70)		Range	0.06–0.77	Lowest ACH occurred in summer with windows closed in R-2000 houses
			R-2000 houses (?)		Range	0.34–0.37	
53	Measured	Sweden	Detached and row houses	1974–1982	Average	0.17	No mechanical ventilation, 1975 and later
			3-story apartments	1974–1982	Average	0.78	No mechanical ventilation, with fireplace, 1940–1960
54	Measured		Houses (typical)		Typical range	0.7–1.1	
			Recently built houses		Typical range	0.5–0.8	
55	Measured	Bangor, WA	2-story, four-unit building (4)		Range	0.24–0.91	Electric heating
22	Measured PFT	Eastern Washington	Houses (10)		Range	0.3–1.0	During typical meterological conditions extended use of doors caused ACH to exceed 3
56	Measured	USA	Houses	N/A	Typical range	0.2–2	
					Median	0.5, 0.9	Median values for two studies
57	Mostly predicted	North America	Houses (312)	N/A	Average	0.63	Mostly predicted using LBL model (stack and wind effect)
					Median	0.5	

Note: PFT = perfluorocarbon tracer, HCB = hexafluorobenzene, SF_6 = sulphur hexafluoride, N_2O = nitrous oxide; Region 1: heating degree days > 7000 (coldest region), Region 2: 5500 < heating degree days < 7000, Region 3: 2500 < heating degree days < 5500, Region 4: heating degree days < 2500.

Table 2. (cont.)

Ref.	Data Type	Location	Building Type and Number	Measurement Date	Measurement Statistic	Air Exchange (ACH)	Comments
16	Predicted AIM-2 HOT-2000	Canada	Houses (47)	Annual average	Average	0.36	R-2000 houses, high energy efficiency houses
					Median	0.34	Use heat recovery ventilators
					Minimum	0.14	
					Maximum	0.68	
58	Measured SF_6	Malmo, Goteburg, Sweden	Office buildings (4)	Jan 1990–Dec 1991	Range	3.2–4	Measured during periods of mechanical ventilation
59	Measured SF_6	Washington, DC	Old-age home	Winter 1983		1.72 ± 0.41	High ACH attributed to excessive heating and cold outdoor temperatures
			School	1983		0.85 ± 0.31	
			Office	July 1983		0.61 + 0.32	
			Office	Sept 1983		0.52 + 0.25	
18	Guidance	Canada	Wood frame pre–1945	N/A	Typical range	0.5–1	Estimated heating season natural ventilation
					Typical range	None	Estimated mechanical ventilation
			Wood frame 1946–1960	N/A	Typical range	0.2–0.4	Estimated heating season natural ventilation
					Typical range	None	Estimated mechanical ventilation
			Wood frame 1961–1980	N/A	Typical range	0.15–0.3	Maybe 0.2 intermittent
			Airtight new house	N/A	Typical range	0.05–0.1	0.3 installed capacity
60	Guidance	Canada	Houses	N/A	Low	0.1	Low
					Typical	0.3	Typical

Note: PFT = perfluorocarbon tracer, HCB = hexafluorobenzene, SF_6 = sulphur hexafluoride, N_2O = nitrous oxide; Region 1: heating degree days > 7000 (coldest region), Region 2: 5500 < heating degree days < 7000, Region 3: 2500 < heating degree days < 5500, Region 4: heating degree days < 2500.

cases, larger-scale test rooms or houses have been used to validate models developed.[5] The interaction between VOCs and building surfaces is complex. Sinks, such as wallboard, ceiling tile, carpet, and upholstery, are important in controlling VOC levels over extended periods. During high-concentration periods, adsorption of VOCs can reduce peak concentrations; however, accumulated VOCs can be released as indoor air concentrations decrease, or as a result of changes in temperature or other environmental factors.[21]

Several indoor air quality studies providing information for houses are summarized in the following section. The VOC concentrations for typical chemicals of concern at contaminated sites have been extracted from these studies and are presented in Table 4. Indoor VOC concentrations were measured in 757 homes from various parts of Canada as part of a comprehensive Health Canada study between 1991 and 1992.[30] Samples were collected using passive devices, and concentrations were quantified by GC/MS. The arithmetic mean total VOC (TVOC) concentration was 829 μg/m^3 based on identified compounds; however, the concentration was estimated to be as high as 1.4 μg/m^3 if non-identified compounds were to be included (i.e., estimate based on area under the gas chromatograph trace). The mean indoor benzene concentration for this study was 5.4 μg/m^3. On the basis of this study, it was concluded that toluene, ethylbenzene, xylenes, decane, and dichlorobenzene were chemicals with a high likelihood of originating from indoor sources; benzene had a medium likelihood; and tetrachloroethylene, trichloroethylene, and hexane had a low likelihood of indoor sources.[6]

The U.S. Environmental Protection Agency (EPA) conducted a comprehensive evaluation of personal (i.e., mostly indoor) air quality for several urban centers, located primarily in industrialized areas (Elizabeth-Bayonne, NJ, and Los Angeles, CA).[31] Passive personal air samplers were used to measure VOC concentrations. The mean concentrations for several compounds (e.g., benzene) were somewhat higher for this study when compared with others summarized in Table 4. Personal air values generally exceeded outdoor air values by ratios of 2 to 5.[31] A summary of VOC concentrations for numerous U.S. studies for all indoor air settings, with the majority of sites corresponding to residential and commercial types, is also available.[32] The mean and median indoor benzene concentrations for this study[32] were 16.5 and 10 μg/m^3, respectively.

Indoor air concentrations were measured in 44 homes in the greater Toronto area (Ontario, Canada) between February 12 and April 9, 1996, using similar methods as the Health Canada study.[33] The mean TVOC concentration was 132 μg/m^3 for this study[33] (based on 20 identified compounds). The mean indoor/outdoor (I/O) ratios for VOCs generally ranged between 1 and 6, and it was 1.79 for benzene.

Table 3. Dominant sources of selected VOCs (adapted from refs 61 and 62).

Source	Benzene	Toluene	Ethylbenzene	Xylenes	Styrene	Trimethylbenzenes	Naphthalene	Trichloroethylene	Trichloroethanes	Tetrachloroethylene	Chlorobenzenes	Decane
Latex paints	X	X				X						
Alkyl paints										X	X	
Carpets	X	X			X	X						
Glued carpets	X	X			X	X					X	X
Wood burning		X		X	X	X	X					
Foam board											X	
Paint removers		X										
Spray products				X								
Adhesives/tape		X			X			X				X
Room deodorizers											X	
Tobacco smoke	X	X	X	X	X							
Gasoline/driving	X	X		X	X	X						
Solvents		X	X									
Dry cleaning									X			

Note: Dominant or key sources of VOCs based on factorial analysis between documented sources in homes and concentrations for Health Canada study. There are other sources of VOCs listed. VOCs selected for table are those commonly found at contaminated sites.

Several studies indicate that VOC concentrations in indoor air can be very high in new buildings.[24,34] For example, TVOC concentrations in new and recently renovated buildings in Switzerland ranged from 1.6 to 31.7 mg/m^3, and were particularly high in buildings with low ventilation rates. Many of the individual compounds detected had I/O ratios that were much higher than 1, and were attributed to materials such as glues, sealants, carpets, and paints. One exception was benzene, which had an I/O ratio of about 1. A Dutch study of 300 homes found that VOC concentrations were significantly higher in newer houses.[35] The I/O ratios for this study[35] ranged from 1 to 10 for most compounds.

ISSUES FOR THE USE OF INDOOR AIR MEASUREMENTS TO QUANTIFY SOIL VAPOR SOURCES

The sampling and analysis methods used for indoor air quality studies referenced in Table 4 were mostly passive or active collection of VOCs on sorbents followed by GC/MC analysis. Sorbents consisted of charcoal, Tenax [poly (2,6-diphenyl phenylene oxide)], or multi-bed sorbent tubes containing graphitized carbons and carbon molecular sieve sorbents. Samples collected using sorbent tubes were often collected over two 12-hr periods to obtain "daytime" and "nighttime" samples, or over a 24-hr period. The recent trend in the United States is the collection of indoor air samples using Summa passivated stainless steel canisters and analysis by EPA method TO-14 or TO-15, as reflected by protocols developed or under development by the commonwealth of Massachusetts[36] and the state of Colorado.[37] The concerns surrounding use of sorbant tubes include chemical breakthrough, cross-contamination, and detection limits that are not sufficiently low. While the mechanics of sample collection and analysis are not overly difficult, the design of an indoor air sampling program and interpretation of data to quantify potential soil vapor sources and risk is a challenging undertaking. Some considerations that we believe will result in improved assessments are discussed in the following sections.

Recognize the High Background VOC Concentrations in Air and Concentration Variability

We are aware of only a very limited number of published studies in which the soil vapor-derived component of indoor air has been thoroughly evaluated. In one study, it was shown that the mean indoor benzene concentration in houses directly above a benzene vapor plume was less than that in nearby control houses in an uncontaminated area.[38] Although there is limited data, the contribution of VOCs from subsurface sources relative to that from indoor sources is expected to be small for most chemicals and sites. Therefore, it is important to recognize the high degree of variability in indoor air quality

Table 4. Compilation of indoor air quality data.

Study	Date and Time	Statistic	Number	Concentrations in Indoor Air: Benzene	Toluene	Ethylbenzene	m,p-Xylene	o-Xylene	Styrene	1,3,5-Trimethylbenzene	Naphthalene	1,2-Dichloroethane	1,1-Dichloroethylene	Trichloroethylene	Tetrachloroethylene	1,1,1-Trichloroethane	m,p-Dichlorobenzene	Carbon Tetrachloride	n-Hexane	n-Heptane	n-Octane	n-Nonane	n-Decane	n-Undecane	n-Dodecane
Lowry AFB Study (Ref 63)[a]																									
Colorado	1997-1998	Median	12-26	-	-	-	-	-	-	-	-	-	<0.012	0.17	0.71	-	-	-	-	-	-	-	-	-	-
		Arithmetic mean	12-26	-	-	-	-	-	-	-	-	-	0.024	0.50	1.1	-	-	-	-	-	-	-	-	-	-
		Maximum	12-26	-	-	-	-	-	-	-	-	-	0.33	2.6	3.5	-	-	-	-	-	-	-	-	-	-
Redfields Colorado Study (Ref 64)[a]																									
Redfields, Denver, CO	1999	Median	55-78	-	-	-	-	-	-	-	-	<0.04	<0.02	<0.26	1.35	1.55	-	-	-	-	-	-	-	-	-
		Arithmetic mean	55-78	-	-	-	-	-	-	-	-	0.074	0.043	0.59	3.65	4.45	-	-	-	-	-	-	-	-	-
		90th percentile	55-78	-	-	-	-	-	-	-	-	0.15	0.06	1.2	6.8	9	-	-	-	-	-	-	-	-	-
		Maximum	55-78	-	-	-	-	-	-	-	-	1	0.48	4.2	50	78	-	-	-	-	-	-	-	-	-
Denver Colorado Study (Ref 65)[a]																									
Denver, CO	1997-1999	Lognormal mean	55-415	4.71	-	-	-	-	-	-	-	0.067	0.022	0.33	-	1.89	-	-	-	-	-	-	-	-	-
		95% tolerance limit	55-415	12.2	-	-	-	-	-	-	-	0.16	0.036	1.08	-	6.98	-	-	-	-	-	-	-	-	-
		Maximum	55-415	41	-	-	-	-	-	-	-	0.48	0.08	16	-	78	-	-	-	-	-	-	-	-	-
Health Canada Study (Ref 6)[b]																									
Across Canada	1991, 1992	Arithmetic mean	757	5.4	40.8	8.2	20.7	5.6	0.3	2.7	-	<0.1	-	0.5	2.7	-	18.9	-	1.2	-	-	-	31.4	-	-
	All seasons	Maximum	757	67.9	5730	540	1470	320	130	640	-	1.7	-	165	313	-	1390	-	124	-	-	-	6450	-	-
EPA TEAM Study (Ref 31)[c]																									
Elizabeth-Bayonne, NJ	Fall 1981	Arithmetic mean	340	28	-	19	52	16	8.9	-	-	-	-	13	45	94	45	9.3	-	-	-	-	-	-	-
	Fall 1981	Maximum	85	120	-	320	120	46	54	-	-	-	-	47	250	880	920	14	-	-	-	-	-	-	-
	Summer 1982	Arithmetic mean	150	-	-	9.2	37	12	2.1	-	-	-	-	6.3	11	67	50	1	-	-	-	-	-	-	-
	Summer 1982	Maximum	71	-	-	180	150	100	10	-	-	-	-	59	98	120	1600	6	-	-	-	-	-	-	-
	Winter 1983	Arithmetic mean	49	-	-	12	36	13	2.4	-	-	-	-	4.6	28	45	71	1	-	-	-	-	-	-	-
	Winter 1983	Maximum	8	-	-	32	63	24	11	-	-	-	-	7	72	170	120	-	-	-	-	-	-	-	-
Los Angeles, CA	Feb 1984	Arithmetic mean	110	18	-	11	28	13	3.6	-	-	-	-	7.8	16	96	18	1	-	-	5.8	-	5.8	5.2	2.5
	Feb 1984	Maximum	25	49	-	29	58	34	9	-	-	-	-	50	94	200	210	3	-	-	38	-	11	11	10
Los Angeles, CA	May 1984	Arithmetic mean	50	9.2	-	7.4	24	7.2	1.8	-	-	-	-	6.4	15	44	13	0.8	-	-	4.3	-	3.5	4.2	2.1
	May 1984	Maximum	25	29	-	35	94	29	5	-	-	-	-	11	56	94	170	1	-	-	20	-	17	76	57
Contra Costa, CA	June 1984	Arithmetic mean	67	7.5	-	3.7	11	4.4	1	-	-	-	-	3.8	6.6	16	5.5	1.3	-	-	2.3	-	2	2.7	2.1
	June 1984	Maximum	10	22	-	9	26	11	4	-	-	-	-	4	9	14	9	3	-	-	2	-	26	16	5
U.S. National Survey (Ref. 32)																									
Across United States	pre-1988	Median	96-2278	10.0	6.3	4.8	-	-	-	1.4	-	-	-	0.7	5.0	10.0	1.7	0.0	-	-	2.4	3.7	1.6	1.8	-
		Arithmetic mean	96-2278	16.5	27.9	12.4	-	-	-	2.8	-	-	-	7.2	20.8	267.4	24.0	2.6	-	-	4.1	6.1	4.5	4.8	-
		Upper quartile	96-2278	21.1	28.8	9.3	-	-	-	4.0	-	-	-	4.5	11.0	30.1	5.6	0.9	-	-	4.3	6.3	4.1	3.8	-
Dutch Study (Ref 35)[d]																									
Ede, Netherlands	Winter 1981/1982	Median	100	7	40	3	12	-	-	2	-	-	-	<2	<2	-	2	-	4	3	2	4	9	5	2
post-war		Maximum	100	148	697	45	178	-	-	99	-	-	-	106	205	-	139	-	107	68	60	269	433	191	118
Rotterdam, Netherlands	Winter 1982/1983	Median	100	7	23	2	9	-	-	1	-	-	-	<2	<2	-	<0.6	-	5	3	1	3	8	3	1
pre-war		Maximum	100	24	526	117	159	-	-	37	-	-	-	11	49	-	355	-	338	30	36	278	807	229	40
Ede, Netherlands	Winter 1982/1983	Median	100	5	43	2	10	-	-	2	-	-	-	<2	<2	-	<0.6	-	3	2	1	6	14	9	4
<6 years		Maximum	100	53	2252	138	753	-	-	93	-	-	-	30	182	-	246	-	178	556	533	407	905	445	96
Greater Toronto Study (Ref 33)[e]																									
Greater Toronto	Feb 12-April 9, 1996	Arithmetic mean	44	3.42	15.2	1.58	-	-	-	0.53	4.81	-	-	-	1.59	-	53.4	-	5.24	-	-	-	6.85	-	-
		Maximum	44	45.8	186	20.9	-	-	-	1.47	83.4	-	-	-	9.55	-	1600	-	108	-	-	-	91.9	-	-
Saskatchewan and Ontario Study (Ref 25)[f]																									
Regina, Saskatoon, SK	Jan 14, 1999-	Arithmetic mean	44	15	23.9	9.6	21.6	5.7	4.1	5.1	7.2	7.4	-	2.3	8.2	-	12.8	-	14.5	-	-	-	-	-	14.7
Tillsonburg, ON	Feb 11, 1991	Maximum	44	42.3	110.5	32.9	74.2	20.3	11.3	15	30	25	-	6.5	30	-	337.5	-	99.4	-	-	-	-	-	91.9
Tennessee Houses (Ref. 66)[g]																									
East Tennessee houses	Aug 1984-Jan 1985	Median	8	7.5	38.5	6.5	18.5	6	-	-	-	0.6	-	0.5	14.5	3.5	0.75	0.5	9	-	-	-	-	-	-
		Maximum	8	30	111	82	302	323	-	-	-	27	-	6	96	18	34	4	113	-	-	-	-	-	-

Note: [a]SummaTM steel canisters and EPA Method TO-14 or TO-15; [b]OVM 3500 (3M Co.) passive samplers, 24-hr samples, quantified by GC/MSD; [c]Personal air samplers using Tenax, arithmetic mean of 12-hr daytime and 12-hr nighttime samples, quantified by GC/MS; [d]Charcoal tubes, 5-7 day samples at 100 mL/min, GC/FID and GC/MS; [e]OVM 3500 passive samplers, 24-hr samples, quantified by GC/MSD; [f]OVM 3500 passive samplers, 24-hr samples, quantified by GC/MSD, 20 houses in SK (Regina and Saskatoon), 24 in Tillsonburg, ON; [g]Sorbent tubes consisting of Tenax or Tenax-carbonaceous mixtures quantified by GC/MS; - = not tested or below detection limit.

when designing an air testing program.

Reported TVOC concentrations, in particular, vary significantly, and range from less than 0.5 μg/m^3 for identified compounds[31-33,35] to ~1.4 μg/m^3 for the Health Canada study, if unidentified compounds are included. This range excludes studies of new houses. The variability, in part, is due to the TVOC definition (identified versus non-identified compounds) and differing analytical methods. For example, polar organics may be lost or underestimated when charcoal or Tenax is used.[34]

The most important determinants affecting indoor air quality are building materials and age and factors relating to occupant use. The design of a background study would need to take these factors into account. Ventilation rates can also affect indoor air concentrations, and therefore, indoor air data collected over various times of the year may not be directly comparable. For example, the Health Canada study[15] indicated that for outdoor temperature ranges of <0 ºC, 0–15 ºC, and >15 ºC, respectively, the mean indoor concentrations for individual VOCs (26 compounds) were 10.3, 9.8, and 5.0 μg/m^3. While these concentration differences were not statistically significant, the trend suggests that the VOC concentrations were affected by outdoor temperature. The apparent difference in VOC concentration was interpreted to be, in part, a result of lower natural ventilation rates during winter months. The trend toward "air-tight" houses and reduced ventilation rates in regions with a cold climate may also be a relevant consideration. Reduced ventilation rates can affect background indoor VOC concentrations, but will not necessarily affect the soil vapor component of indoor concentrations, because building underpressurization and VOC intrusion may also decrease in conjunction with a reduction in ventilation rates. In some cases, mechanical ventilation systems are also designed to minimize their influence on building pressurization.

Recognize the Temporal Variation in Soil Gas Intrusion

Since soil gas advection appears to be the most significant mechanism for VOC intrusion into buildings, there may be diurnal variations in intrusion due to daily temperature fluctuations, longer-term variations due to changes in barometric pressure, and seasonal variations due to differences in temperature and ventilation system operation. As proposed by one researcher,[11] the collection of indoor air samples during periods of both positive and negative soil-to-building pressure gradients may actually provide a means to distinguish between indoor and subsurface sources.

Complementary Data Is Essential

We consider obtaining complementary data to assist in the interpretation of indoor air data as essential, because the "blind use" of measured indoor air concentrations may lead to erroneous conclusions with respect to the VOC source. Measurement data and information that are relatively important and easy to obtain are

(1) Pressure gradients between the basement (or ground floor) and atmospheric air, measured at the time of sampling. Several studies indicate that building depressurization can result in signficant soil gas intrusion through advection.[7,11,39]
(2) Collection of seasonal data when conditions suggest seasonal effects could be significant. For example, for houses in cold climate areas, vapor intrusion rates for an advection-dominated system (i.e., controlled by near-field processes) would be expected to be highest during winter months due to the stack effect.
(3) Description of building features (age, basement, garage); foundations (construction, any visible cracks, drains, sumps, utility connections); heating, ventilation, and air conditioning system type and operation; and occupant use during sampling. If ventilation rates are highly uncertain, tracer tests to measure building ventilation rates can also be considered.
(4) Meterological data, such as precipitation, temperature, barometric pressure, and wind speed. These data are relatively inexpensive to obtain, and can be used to evaluate pressure gradients.

In comparison to the expense and effort required to obtain high-quality indoor air data, obtaining the above data is considered relatively straightforward and cost effective.

Soil vapor concentrations below a building and cross-foundation slab pressures can be highly useful in that they provide a direct indication of vapor sources and advection potential. Obtaining these data may be problematic at occupied houses because of the intrusive nature of such measurements. Nevertheless, it is suggested that these data be obtained at least at a subset of the buildings under consideration, whenever possible. In some cases, soil vapor measurements are obtained at similar depths to the building ground floor slab in an attempt to infer subslab vapor concentrations. Several studies have shown that there can be significant differences between soil vapor concentrations below and adjacent to a building;[38,39] therefore, this approach is not recommended.

Use of Natural Tracers

The use of natural tracers to distinguish between subsurface and building sources may be possible when subsurface

transformations result in chemicals that are not normally found indoors. For example, 1,1-dichloroethylene (DCE), a degradation product of trichloroethylene (TCE), was either not detected or not quantified in the indoor air quality studies reviewed in the previous sections, suggesting that background DCE concentrations in air are low. For a site where both TCE and DCE are measured in soil vapor, and DCE is detected in indoor air, a mass balance approach could be used to approximate the TCE concentrations in indoor air as follows. Assuming VOCs are well mixed, the following mass balance equation for a house, or portion of a house (e.g., basement), is obtained:

$$V dC_i/dt = C_o Q_{in} + M_{sv} - C_i Q_{out} + S_i - R_i \quad (1)$$

where V is the house volume (L^3); C_i and C_o are the indoor and outdoor VOC concentrations, which in this case are for DCE (M/L^3); Q_{in} is the air flow entering the house, M_{sv} is the mass flux of soil vapor VOC entering the house (M/T), Q_{out} is the air flow leaving the house (L^3/T), S_i is the source term, and R_i is the removal (sink) term. If the soil gas flow (Q_{sg}) entering the house is small relative to the building air exchange, if steady-state conditions prevail, and if there are no sources or sinks, the air flow and mass flux of the soil vapor tracer (DCE) can be estimated as follows:

$$Q_{out} = Q_{sg} + Q_{in} \sim Q_{in} \sim V\,ACH \quad (2)$$

$$M_{sv}^{DCE} = V\,ACH\,(C_i^{DCE} - C_o^{DCE}) \quad (3)$$

where ACH is the air changes per hour (L^3/T per L^3). The mass flux of the chemical of interest (TCE) and indoor air concentration associated with a soil vapor source are estimated using the relative concentrations measured in soil vapor

$$M_{sv}^{TCE} = M_{sv}^{DCE}\, C_{sv}^{TCE}/C_{sv}^{DCE} \quad (4)$$

$$C_i^{TCE} = M_{sv}^{TCE}/(V\,ACH) \quad (5)$$

where C_{sv}^{TCE} and C_{sv}^{DCE} are concentrations of TCE and DCE in soil vapor (M/L^3). When near-foundation soil vapor measurements are available, and advection is the dominant mechanism for vapor intrusion, eq 4 is likely a reasonable approximation. If diffusion, sorption, and other processes are important, this relationship would only be accurate if chemical fate and transport were similar between the tracer and chemical of interest.

SIGNIFICANCE OF SUBSURFACE RELATIVE TO INDOOR VOC SOURCES

The potential significance of intrusion of soil vapor containing VOCs into buildings, relative to background indoor air sources, is evaluated using a slightly modified version of the Johnson and Ettinger model.[40] This model is commonly used to predict indoor air concentrations from subsurface contamination sources. Model predictions are made for a range of soil and building properties and a single vapor concentration at the contamination source (i.e., single source strength).

The Johnson and Ettinger modeling results are given as a function of the vapor attenuation ratio (α) and the ratio of effective diffusion coefficient (D_T^{eff}) to depth to contamination (L_T) (see Figure 1). The α value is defined as the indoor air concentration divided by the source vapor concentration. The D_T^{eff}/L_T ratio captures the influence of soil properties and depth to contamination source on α. Since free-air diffusion coefficients vary by only a factor of 2 for most volatile chemicals, chemical-specific variation in the D_T^{eff}/L_T ratio will be of little consequence in most cases.

The influence of building foundation and building properties are represented by a possible "upper" and "lower" range of input values, considered representative of most sites (Figure 2). These values were subjectively chosen based on the authors' research and review of other studies.[39,41] The building mixing height is the height over which mixing of soil vapor contaminants take place. The assumed range corresponds to a one- to two-story house. The slight modification to the model is that the advective soil gas flow rate (Q_{soil}) is directly input, and not estimated using the equation referenced by Johnson and Ettinger.[40] The Q_{soil} range is roughly based on measured

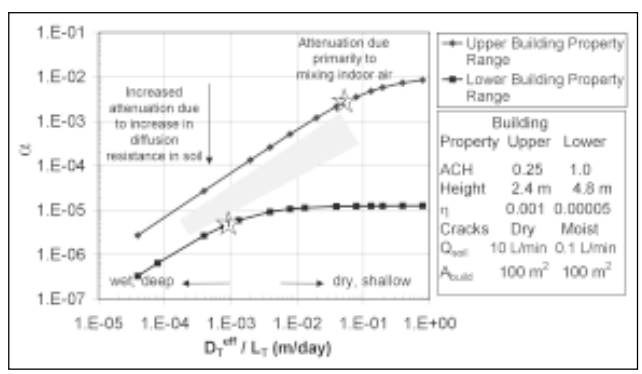

Figure 2. Vapor attenuation between benzene vapor concentrations at source, and indoor air predicted using the Johnson and Ettinger model.[40] Figure adapted from ref 45. The shaded region is considered to encompass the majority of sites. Height = building mixing height, η = crack ratio, Q_{soil} = advective flow rate into building for coarse-grained soils, total porosity dust-filled concrete cracks = 0.3, water-filled porosity dust-filled concrete cracks = 0.1.

values from tracer tests at several sites for coarse-grained (sand to gravel) soils.[41] The modeling assumes a soil contamination source above the water table. The highest α values are estimated when there is shallow contamination, dry soil (i.e., high air-filled porosity), high advective soil gas flow rates into the building, and low ventilation rates.

Model-predicted indoor air concentrations from soil vapor are estimated for benzene, TCE, and TVOC (Figure 3). The assumed source vapor concentrations are possible "typical" values based on reported concentrations for several studies (Table 5). The assumed background indoor air concentrations are mean concentrations measured for the Health Canada study.[6]

The incremental lifetime cancer risk (ILCR) is estimated for benzene and TCE using reported Health Canada tumorigenic concentrations corresponding to 5% cancer incidence (TC_{05}).[42] The tumorigenic concentrations are based on neoplastic effects in animal species, and animal-to-human conversions that incorporate inhalation to body weight ratios. These conversions are based on variations in breathing rates and body weights between rodents and the age group for humans for which this ratio is greatest (i.e., ages 5–11). Health Canada considers benzene as a Group 2 chemical (carcinogenic), while TCE is classified as Group 20 (probably carcinogenic).[42] The ILCR is calculated as follows:

$$\text{ILCR} = 0.05\ C\ ET\ EF/(TC_{05}\ UCF) \qquad (6)$$

with C equal to the indoor air concentration, and other exposure and risk parameters defined in Table 6. The ILCR is estimated using the predicted indoor air concentration derived from both soil vapor and the background benzene and TCE concentrations measured for the Health Canada study[6] (Figure 4). While regulatory promulgated toxicity values for TVOCs are not available, numerous studies have attempted to evaluate health effects associated with TVOC.[24] For example, Molhave and coworkers[43,44] reported sensory effects at a TVOC concentration of 1.7 mg/m^3, dose effects for odor starting at 3 mg/m^3,

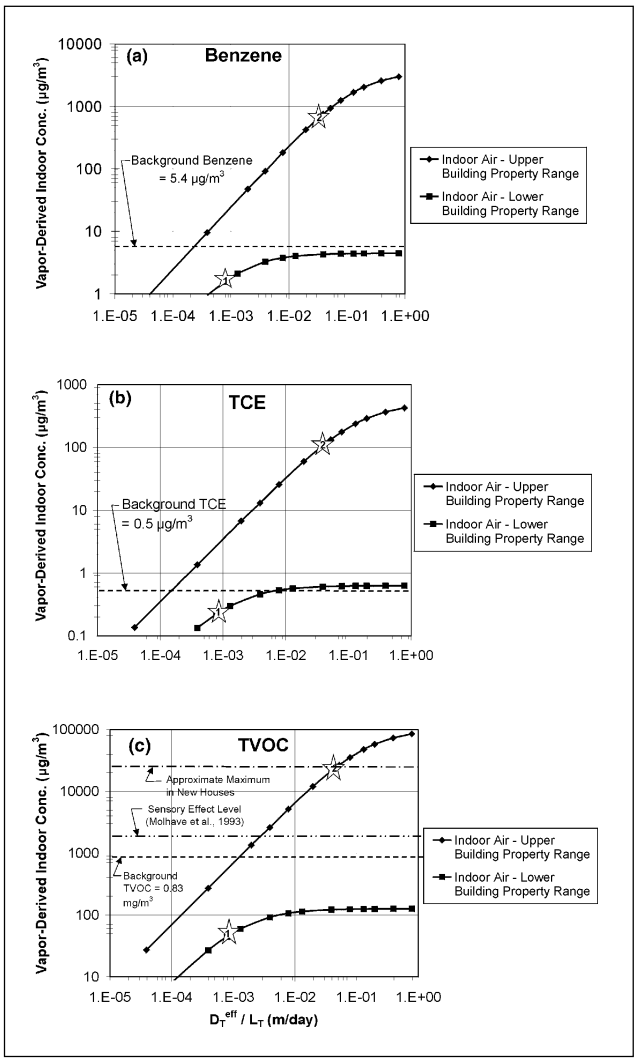

Figure 3. Model-predicted vapor-derived indoor air concentrations for (a) benzene, (b) TCE, and (c) TVOC. The soil vapor component of the indoor air concentration was predicted using the Johnson and Ettinger model.[40]

Table 5. Assumed soil vapor concentrations at contamination source used for modeling.

Chemical	Reference	Contamination Type[a]	Approx. Measured Vapor Concentrations (µg/L)[b]
Benzene	20	Gasoline	200
	36	Gasoline	576
	67	Gasoline	270–300
Assumed Benzene Source Vapor Concentration:			**350**
TCE	68		18
	69	PCE, TCE	3
	70	PCE, TCE	50
Assumed TCE Source Vapor Concentration:			**25**
TVOC	4	Gasoline	10,000
	20	Gasoline	40,000
	71	Aviation fuel	6400–40,000
	72	Gasoline	10,000
Assumed TVOC Source Vapor Concentration:			**10,000**

Note: [a]Vapor concentrations for all sites were measured near to the water table. For gasoline and aviation fuel sites, residual NAPL was in close proximity to probes (i.e., above water table). For chlorinated solvent sites, vapor probes were near source locations; however, presence of residual NAPL above water table is less certain (concentrations may reflect a dissolved groundwater source); [b]Most values are peak vapor concentrations; however, in some cases, only limited soil vapor data was available.

Table 6. Exposure and risk factors.

Factor	Value
Exposure time (ET, hr/day)	20
Exposure frequency (EF, day/year)	350
Exposure duration (ED, year)	30
Averaging time carcinogens (years)	75
Unit conversion factor (UCF, hour to year)	8760
Benzene TC_{05} (mg/m^3)[a]	15
TCE TC_{05} (mg/m^3)[b]	140

Note: [a]Health Canada (1996);[42] [b]TCE TC_{05} is average of three reported values.

and reduced well-being at greater than 25 mg/m^3 TVOC.

The significance of the model predictions are compared for two hypothetical sites with identical contamination sources and the source vapor concentrations in Table 5, but with differing site characteristics, as follows:

Site 1: Depth to contamination = 5 m
Moist soil (water-filled porosity = 0.2)
Low advection potential = Lower-range building properties (Figure 2)

Site 2: Depth to contamination = 1 m
Dry soil (water-filled porosity = 0.1)
High advection potential = Higher-range building properties (Figure 2)

In both cases, the total soil porosity is taken to be 0.3.

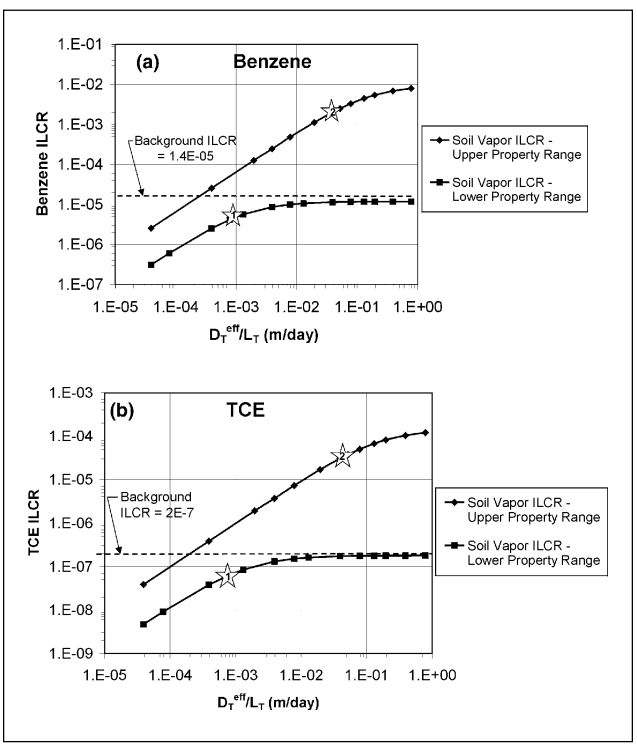

Figure 4. Predicted incremental lifetime cancer risks using soil vapor-derived indoor air concentrations in Figure 3 for (a) benzene and (b) TCE.

Model parameters for sites 1 and 2 are shown in Figure 2. The α values for sites 1 and 2 are about 7E-06 and 3E-03, respectively. The importance of advection potential and building properties (i.e., the essential "complementary" data described earlier) is highlighted in Figure 2. The implication of the site 1 results is that the model-predicted indoor VOC concentrations from soil vapor are less than the background indoor concentrations. Of note is that the background ILCR for benzene is relatively high (1.4E-5). For site 2, the predicted indoor benzene and TCE concentrations from soil vapor are more than 2 orders of magnitude greater than background indoor air concentrations. For TVOC, the difference between indoor concentrations from soil vapor and background sources is not as great, and the soil vapor-derived indoor air concentration is similar to maximum TVOC levels expected for new houses. The model predictions for site 2 suggest that soil vapor-related risks may be significant for sites with shallow contamination and high advection potential. This conclusion is predicated upon theoretical model predictions for possible vapor source strengths, and does not consider how well the Johnson and Ettinger model predicts soil vapor transport and intrusion into buildings. The accuracy and validation of models for this pathway goes beyond the intended scope of this paper, but has been addressed elsewhere.[45,46]

CONCLUSIONS

Soil vapor intrusion into buildings is complex, highly dependent on site-specific conditions, and can vary over time. There are numerous other significant sources of VOCs beyond soil vapor, and the reported range in background indoor VOC concentrations is large. Understanding mechanisms for soil gas intrusion is important when indoor air measurements are used to deduce the subsurface-derived component, since for most sites, the contribution from soil vapor is likely to be small relative to other sources. Model-predicted indoor air concentrations from soil vapor are compared to background indoor concentrations, and show that the relative importance of soil vapor will depend on site-specific conditions. For deep contamination, where diffusive transport is the dominant process [far-field condition (see Figure 1)], indoor air concentrations and risk from soil vapor will tend to be insignificant relative to risks associated with background indoor VOCs. In contrast, for shallow contamination, where advective transport is the dominant process [near-field condition (see Figure 1)], model predictions suggest that indoor air concentrations and risk from soil vapor could be significant. Since distinguishing the subsurface vapor component from background indoor sources will, in practice, be difficult for most sites, appropriate sampling strategies should be used. This includes collection of

essential complementary data and information on pressure gradients, seasonal data, house characteristics, meteorological data, and whenever possible, subslab vapor concentrations.

Further work is required to evaluate how indoor air measurements can best be used to quantify potential exposure and risk from subsurface VOCs. This includes studies that generate high quality and comprehensive data sets for soil vapor, indoor air in impacted and background areas, and information on factors that affect soil vapor intrusion and indoor air quality. Also needed is further development of protocols for indoor air sampling when the goal is to estimate vapor-derived indoor air concentrations.

ACKNOWLEDGMENTS

This research represents one part of a comprehensive study of the soil vapor transport to indoor air pathway, sponsored by a consortium of governmental agencies and industry partners consisting of Alberta Environmental Protection, American Petroleum Institute, B.C. Environment, B.C. Science Council, Canada Housing and Mortgage Corporation, Canadian Association of Petroleum Producers, Canadian Petroleum Products Institute, Chatterton Petrochemical, Dow Chemical, Golder Associates Ltd., and Ontario Ministry of Environment.

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