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Critical Review

Vapor Intrusion Investigations and Decision-Making: A Critical Review

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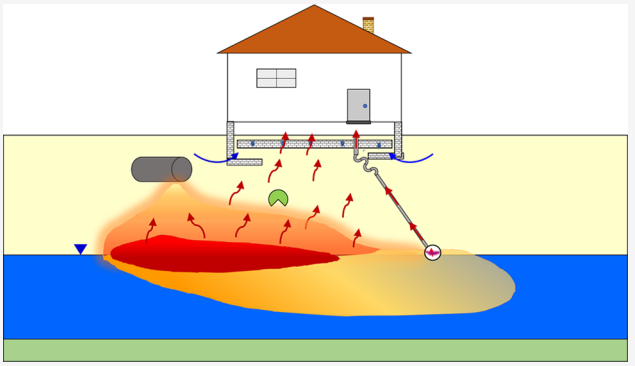
ABSTRACT: At sites impacted by volatile organic compounds (VOCs), vapor intrusion (VI) is the pathway with the greatest potential to result in actual human exposure. Since sites with VI were first widely publicized in late 1990s, the scientific understanding of VI has evolved considerably. The VI conceptual model has been extended beyond relatively simple scenarios to include nuances, such as biological and hydrogeological factors that may limit the potential for VI and alternative pathways, such as preferential pathways and direct building contact/infiltration that may enhance VI in some cases. Regulatory guidance documents typically recommend initial concentration- or distance-based screening to evaluate whether VI may be a concern, followed by a multiple-lines-of-evidence (MLE) investigation approach for sites that do not screen out. These recommendations for detailed evaluation of VI currently focus on monitoring of VOC concentrations in groundwater, soil gas, and indoor air and can be supplemented by other lines of evidence. In this Critical Review, we summarize key elements important to VI site characterization, provide the status and current understanding, and highlight data interpretation challenges, as well as innovative tools developed to help overcome the challenges. Although there have been significant advances in the understanding of VI in the past 20 years, limitations and knowledge gaps in screening, investigation methods, and modeling approaches still exist. Potential areas for further research include improved initial screening methods that account for the site-specific role of barriers, improved understanding of preferential pathways, and systematic study of buildings and infrastructure other than single-family residences.



1. INTRODUCTION

Vapor intrusion (VI) is the migration of volatile chemicals from contaminated soil or groundwater into buildings.[1] VI is considered to be the most important human exposure pathway at sites impacted by volatile organic compounds (VOCs) because, at most sites, it is the pathway with the greatest potential to result in actual human exposure.[1,2] Since the VI pathway became more widely recognized in the late 1990s in the United States (US), this exposure pathway has been attracting increasing attention from regulatory, industrial and academic communities in many countries.[2] In 2002, the United States Environmental Protection Agency (USEPA) issued draft guidance documents addressing the VI pathway.[3] However, final guidance was not issued until 2015 after 13 years of debates and modifications.[4,5] These and other guidance documents from different countries and institutions are summarized in Tables S1 and S2. In 2018, for the first time in history, the USEPA added two sites to the National Priorities List (Superfund) based solely on VI risk.

Several review papers on VI of chlorinated and petroleum VOCs have been published.[6−15] However, these papers either predate notable developments in the understanding of VI[6,8,10,11] or focused on only specific aspects of VI problems.[7,9,12−15] Based on the rapidly evolving recognition of the VI pathway, associated global demands for regulatory guidance, and fundamental advancements in the understanding of the VI conceptual model and its characterization, a comprehensive review that critically analyzes the latest science on VI with a focus on investigation and decision-making practices is warranted. The primary goals of this paper are to summarize the state of the practice and provide perspectives on critical knowledge gaps to improve risk assessment.

2. VAPOR INTRUSION CONCEPTUAL MODELS

A **conceptual model** combines site-specific information with theoretical knowledge and practical experience from similar sites to form a framework to describe the fate and transport processes of contaminants from sources via pathways to receptors. After

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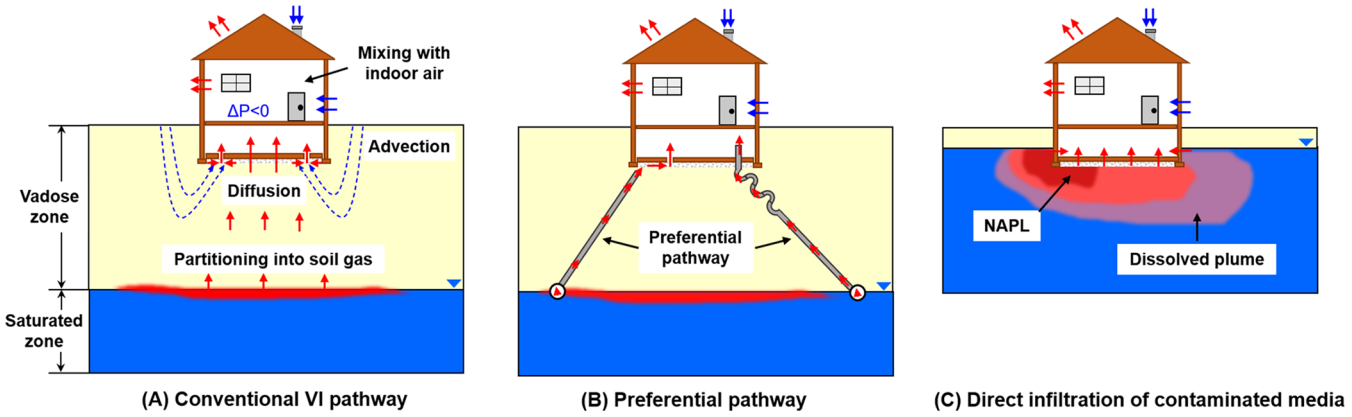

Figure 1. Various types of VI conceptual models: (A) conventional VI pathway, (B) preferential pathway, and (C) direct building contact.

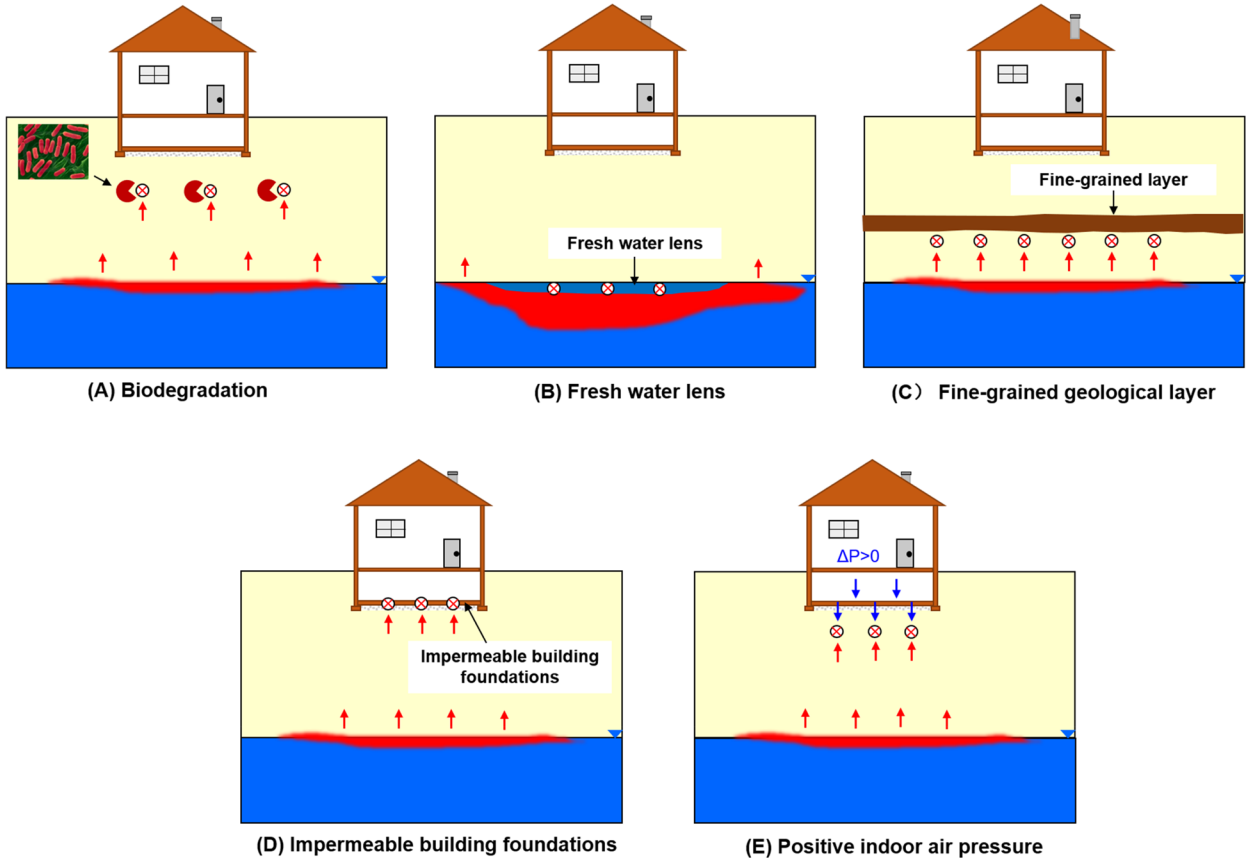

Figure 2. Common barriers for conventional VI include: (A) rapid biodegradation of VOCs in the vadose zone, (B) fresh water lens on top of the water table, (C) low permeable geological zone in the vadose zone, (D) impermeable building foundations, and (E) positive indoor air−subslab gas pressure difference.

more than two decades of extensive studies, fundamental improvements in the scientific understanding of VI pathways have helped shape data collection and our understanding of the VI conceptual model. This **VI conceptual model** (section 2.1) has been extended to include **preferential pathways** (section 2.3) and **direct infiltration of contaminated media** (section 2.4) (Figure 1).

2.1. Basic Conceptual Model for Conventional Vapor Intrusion. The **basic conceptual model of VI** covers the following processes: (1) VOC partitioning from a soil or groundwater source into soil gas; (2) diffusion through the vadose zone from the source to the area near the building foundation, certain VOCs, particularly petroleum VOCs, may also be attenuated by biodegradation during diffusive migration in the vadose zone; (3) advection and diffusion through cracks, holes and seams in the slab and walls into the building; and (4) mixing with indoor air at the point of exposure (Figure 1A). Although the VI pathway has many complexities, this basic conceptual model captures the key processes, particularly with respect to chlorinated VOC sites. On the basis of modeling and empirical data, certain VOCs, regulatory guidance typically recommends evaluation of VI for buildings located up to distances of 100 feet from subsurface VOC sources,[4,5,16] particularly for chlorinated VOCs sources.

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Gas-phase diffusion through air-connected porous soils is generally considered the dominant physical transport mechanism in the vadose zone affecting VOC transport through the vadose zone (e.g., >1 m below the building foundation). Soil gas advection has been associated with fluctuations in barometric pressure and biogenic gas production from methanogenic biodegradation.[17−19] For many buildings, the relative significance of gas-phase advection increases near and through building foundations because pressure gradients across the building foundation drive advective VOC transport (Figure 1A).[20,21] Recently, bubble-facilitated vapor intrusion is attracting more attention.[22−24] More field studies are needed to understand the significance and universality of this pathway.

The driving force of vapor entry by advection is gas pressure gradients across the building foundation caused by a combination of **wind effects**, **stack effects**, and **mechanical ventilation** (Figure S1).[25−32] Inside the building, VOCs undergo mixing and dilution that is influenced by mechanical air circulation and the **indoor air exchange rate (AER)**, which is an important parameter that determines the VOC concentration in indoor air.[25,26,30,33−35] More information on wind effects, stack effects, mechanical ventilation, and indoor AER can be found in Texts S1 and S2.

The conventional VI conceptual model adopts the assumption from the radon intrusion conceptual model that advection is the dominant chemical transport pathway across building foundations (Figure 1A).[20,21] However, radon has shorter half-life (only 3.8 days) while typical VOCs are relatively persistent in the environment. As a result, diffusion may play a more important role in the VOC migration across the building envelope for building foundations that lack cracks or other penetrations that allow for advective flow. Diffusive transport through a building foundation has been most clearly observed for buildings with high subslab soil gas VOC concentrations (e.g., >100 000 $\mu g/m^3$). For example, a field study showed that diffusive transport through a slab-on-grade building foundation was the dominant VI pathway when the building was under ambient pressure conditions.[36] When the building indoor air pressure was mechanically reduced, advective transport became the dominant pathway.[36] Additional research is needed to more accurately identify buildings where diffusive versus advective transport is the dominant pathway across the building foundation.

2.2. Barriers to Conventional Vapor Intrusion. The presence of VI barriers may prevent vapor migration and significantly reduce the potential for VI such that, at some sites, the subsurface source zone contains high concentrations of VOCs while the indoor air concentrations in overlying buildings are relatively low.[37] Factors that limit conventional VI include rapid biodegradation of VOCs in the vadose zone (section 2.2.1), fresh water lens (section 2.2.2), fine-grained geological layers (section 2.2.3), impermeable building structures (section 2.2.4), and positive indoor air pressure (section 2.2.5) (Figure 2).

2.2.1. Biodegradation. Field experience has demonstrated that **petroleum VOCs (pVOCs)** pose a much lower vapor intrusion risk than **chlorinated VOCs (cVOCs)**. This difference is attributed to relative differences in biodegradability.[38] Microorganisms that are capable of degrading certain hydrocarbons are ubiquitous in soil and groundwater.[39,40] These hydrocarbons can be biodegraded both aerobically and anaerobically, but aerobic biodegradation is more energetically favorable and is typically much faster than anaerobic biodegradation. A number of studies have demonstrated that aerobic biodegradation in the vadose zone can significantly reduce the VI potential of pVOCs (Figure 2A).[41−43] These studies show that pVOCs degrade over a short vertical distance (1−2 m) in the vadose zone when sufficient oxygen is present (>2% v-v). Updated regulatory guidance[5] and mathematical models[44,45] for petroleum vapor intrusion have incorporated aerobic biodegradation to more accurately predict the potential for VI from pVOCs.

In the context of vapor intrusion evaluations, cVOCs are considered to be recalcitrant to biodegradation in the aerobic vadose zone.[38] However, a number of studies have observed that less-than-fully chlorinated aliphatic hydrocarbons (e.g., dichloroethene (DCE), vinyl chloride (VC), and 1,2-dichloroethane (1,2-DCA)) can be biodegraded aerobically via metabolic or cometabolic pathways at relatively high rates.[46−56] Regarding VC, bacteria capable of its aerobic degradation appear to be ubiquitous[57,58] and, as a result, the VI risk for VC is more comparable to pVOCs than to other cVOCs. USEPA-recommended vertical screening distances for pVOCs (4.6 m) were applicable to screen VI risk of 1,2-DCA and 1,2-dibromoethane (EDB) under certain site conditions.[52,53] Recent studies have also demonstrated the aerobic metabolic degradation of trichloroethylene (TCE) as the sole carbon source by a mixed bacterial consortium[59] and confirmed the long-term stability of aerobic metabolic TCE degradation by the bacterial consortium under a wide range of incubation conditions.[60] Further studies are thus recommended to fully understand the extent to which aerobic biodegradation limits the potential for cVOC VI. The derivation of vertical screening distances for certain key cVOCs may also be possible.

2.2.2. Fresh Water Lens. VOC diffusion through water is orders of magnitude slower than through soil gas. As a result, a layer of water between a VOC source and a building (either at the water table or in the vadose zone) can serve as an effective barrier that prevents VI. In areas with heavy precipitation or artificial recharge (e.g., irrigation), a layer of clean water may accumulate at the interface of the water table and capillary fringe resulting in a **fresh water lens**[61] (Figure 2B). Because of the slow diffusion rate of VOCs in the aqueous phase, a fresh water lens will significantly reduce the off-gassing of VOCs from groundwater.[18,62] Water table fluctuations, however, can enhance the transfer of VOCs from groundwater into the vadose zone,[63−65] potentially reducing or eliminating the effect of a fresh water lens. In addition, trees or other plants with roots that extend to the water table may remove the shallowest groundwater through evapotranspiration resulting in removal of the fresh water lens and exposure of the VOC plume at the top of the water table.[7]

2.2.3. Fine-Grained Geological Layers. A number of studies have documented the effect of high soil moisture on reducing VOC diffusion rates in the vadose zone and reducing VI potential (Figure 2C).[62,66−68] Diffusion rates are significantly lower through water-connected soils versus air-connected soils.[69,70] Field studies demonstrated that the presence of fine-grained silt or clay layers with high enough water content in the vadose zone to break the air-connected diffusion routes resulted in high VOC attenuation from groundwater to deep soil gas. This study found that, at these sites, generic groundwater to soil gas attenuation factor could be adjusted by 100-fold to account for the increased attenuation attributable to these fine-grained layers.[71] However, because VOC diffusion is more strongly influenced by soil moisture than soil types,[72] measuring the

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moisture content of fine-grained layers is an important part of evaluating their effectiveness as a VI barrier.[71]

2.2.4. Building Structures. Certain building designs may prevent the migration of VOCs into the occupied portions of a building (Figure 2D). For example, the presence of a large ventilated underground structure, such as a parking garage creates a pneumatic barrier between the subsurface and the building if there is no elevator to act as a conduit. VOC migration into buildings can also be prevented by passively or mechanically ventilating below the building foundation.[73−75] Sealing building foundations can also act as an effective vapor barrier; however, it may not inhibit VOC migration to indoor air for buildings with preferential pathways that allow for direct VOC entry (see section 2.3).

2.2.5. Positive Indoor Air Pressure. In buildings with consistently positive indoor air−subslab gas pressure differences, the pressure gradient drives the flow of indoor air out of the building. A modeling study shows that even a small constant positive pressure (e.g., 1 Pa) would increase the VOC attenuation by several orders of magnitude (Figure 2E).[76] Many building ventilation systems are designed to maintain positive building pressure to control humidity, dust, and other indoor air quality parameters.[77] However, because wind and stack effects can cause fluctuations in building pressure, it may be important to verify through direct measurement that a particular building does maintain consistently positive pressure.

2.3. Preferential Pathways. There is growing field evidence that preferential pathways can play a critical role in VI. The broad definition of **preferential pathways** is subsurface features with high permeability that can serve as high-capacity pathways or conduits for VOCs migrating from subsurface sources to or into buildings (Figure 1B).[4,78,79] Most building foundations contain openings or structures that create the potential for entry of soil gas located directly adjacent to the building. However, when a preferential pathway provides a conduit for transport of VOCs from a source located away from a building, the migration of VOCs through this preferential pathway may result in higher than anticipated VOC mass flux and indoor air concentrations in overlying buildings.[80,81] In addition, the lateral migration of VOCs through a preferential pathway can result in VI impacts to buildings located outside the footprint of subsurface contamination.[82]

Historically, the term "preferential pathway" has been defined to include man-made conduits (e.g., sewer lines, storm drains, land drains, utility lines, cable ducts, and steam lines), backfill materials outside conduits, and natural geological structures (e.g., fractured rock, karst, and gravel layers). However, a small but growing number of field studies show that sewer lines and other unfilled subsurface utility conduits may be the most important VI preferential pathways.[78−85] It has been estimated that sewer pathways are the dominant VI mechanism in more than 20% of dry cleaner sites in the central Denmark region.[86] Sewer pipes develop cracks, leaking joints, and other damage over time because of corrosion, earth subsidence, pipe settling, and biological intrusion.[87] When cracked pipes intersect contaminated soil or groundwater, VOC-containing fluids (groundwater or soil gas) may infiltrate into the sewer system. Once in a sewer, VOCs can impact indoor air via two possible routes: (1) migration through the plumbing system directly into the building and (2) migration through the sewer pipe to the subslab area and into the building via foundation cracks (Figure 1B). The direct migration can occur when plumbing features designed to prevent the migration of sewer gas into a building fail or when plumbing does not meet typical accepted building practice.

Consideration of relevant preferential pathways is critical for both VI assessment and mitigation. Failure to understand the role of a preferential pathway in VOC transport can result in an incorrect conceptual model for VI and an incorrect mitigation response. Despite its importance, the presence of a preferential pathway is not easily identified by traditional VI investigation methods. For most of the reported sewer VI sites, the importance of the sewer pathways was identified only after obtaining investigation data that could not be explained by the conventional VI conceptual model[4,73] or after conventional VI mitigation methods failed to reduce the indoor air concentration.[80] In many cases, recently developed site investigation technologies show great promise to identify and characterize the preferential pathway (section 4.2).

Although there is growing awareness of the importance of preferential pathways for VI, there is little information in regulatory guidance documents on investigation methods for the evaluation of these pathways. Beckley and McHugh compiled field monitoring data from more than 30 sites and found that the degree of interaction between sewer pipes and subsurface VOC sources was the main factor that determines the degree of risk of sewer VI.[83] Higher risk sites are those with direct interaction between sewer pipes and contaminated soil/groundwater while lower risk sites are those with sewer pipes located above, but separated from, the VOC source.[83] They further proposed investigation protocols for the sewer pathway: conducting standard VI investigation (including indoor air testing) for lower risk sites, but measuring sewer gas early during the VI investigation process for higher risk sites.[83,84] A number of state and local regulatory agencies have referenced or recommended this protocol for the evaluation of preferential pathways.[88,89]

Two studies investigated the spatial and temporal variability of VOC concentration in sewer gas.[82,90] The spatial variability of TCE concentrations in sewer gas ranged from nondetect to 1600 $\mu g/m^3$ over an area of 1300 × 550 m.[82] Temporal variability in TCE sewer gas concentrations was over the time scale from hours (~3-fold difference) to months (>100-fold difference).[82] Because of these variations, interpreting sewer gas data is not necessarily straightforward.

Recently developed site investigation technologies can be used to help identify and characterize preferential pathways (see also section 4.2). Guo et al. used the building pressure cycling (BPC) method in conjunction with other lines of evidence to identify a preferential pathway in a research house.[79] McHugh et al. used compound-specific stable isotope analysis (CSIA) to identify a sewer gas source in a research house.[91] Pennell et al. used sewer gas and indoor air sampling to identify a sanitary sewer pipe as a PCE VI pathway.[81]

2.4. Direct Infiltration of Contaminated Media. For areas with shallow/fluctuating groundwater or perched zones, the contaminated groundwater or NAPL may directly contact the building envelope, which may lead to direct intrusion of these contaminated media into buildings through cracks or by basement drainage systems (Figure 1C).[1] Such infiltration of contaminated media is also possible for underground structures, such as parking garages, subways, and pedestrian and traffic tunnels that are common in densely developed urban areas (Figure S2). This scenario may result in higher vapor concentrations inside the building or structure than would be expected based on advection or diffusion of vapors into the

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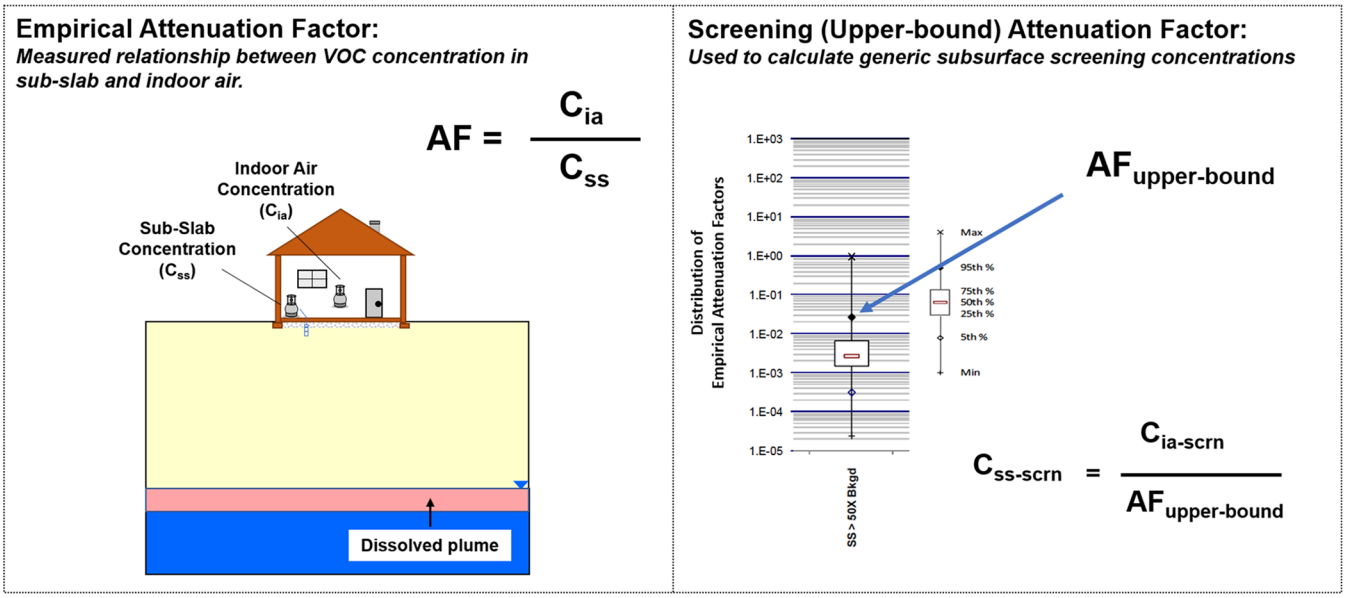

Figure 3. Conceptual illustration of an empirical attenuation factor (AF) and a screening attenuation factor ($AF_{upper\text{-}bound}$). The AF distribution graph was adapted from USEPA (2012).[92] AF = empirical attenuation factor, C_{ia} = measured concentration in indoor air, C_{ss} = measured concentration in subslab, $C_{ia\text{-}scrn}$ = screening level in indoor air, $Cs_{s\text{-}scrn}$ = screening level in subslab, and $AFu_{pper\text{-}bound}$ = screening (upper-bound) attenuation factor.

structure. Although modern construction of structures potentially located below the water table utilizes engineered barriers or hydraulic controls to prevent water infiltration, these controls may be absent in older buildings. When present, some control systems operate in a way that allows the release of volatile contaminants inside the structure (e.g., diffusion through pores in concrete). Compared to the conventional VI pathway and the VI preferential pathway, less research has been focused on the direct building contact/infiltration pathway.

3. VAPOR INTRUSION PATHWAY SCREENING

Within the regulatory context, the VI pathway is considered to be complete if VOCs migrate from the subsurface into a building and result in indoor air concentrations above an applicable regulatory or risk-based concentration limit based on the building use.[4] **Initial screening** of the VI pathway is used to screen out sites with very low risk for VI and to efficiently prioritize areas or buildings that may require further VI assessment.[1] Initial VI screening usually include two methods: **concentration-based screening** (section 3.1) and distance-base screening (section 3.2). These methods may be supplemented with other site factors, such as soil type (section 3.3).

3.1. Concentration-Based Screening. For concentration-based screening, maximum VOC concentrations in groundwater or soil gas are typically compared to VI pathway screening concentrations to determine if further evaluation is needed.[1] **Screening concentrations** are most often developed by regulatory authorities using an **attenuation factor (AF)** approach.[4] **AF** is defined as ratio of the VOC concentration in indoor air to the VOC concentration at some point in the subsurface (e.g., soil gas or groundwater).[2] An **empirical AF** is a ratio of actual measured concentrations at a site. A **screening AF** is a conservative (i.e., upper-bound) AF used to calculate subsurface screening values (Figure 3). Using this approach, the subsurface screening values are calculated as the applicable indoor air concentration limit divided by the screening AF.

Initially, screening AFs were developed using simple analytical models such as the Johnson and Ettinger (J&E) model and consideration of building air exchange rates.[3] More recently, large data sets of **empirical AFs** have also been compiled and upper-bound values from these data sets have been used to support the selection of screening AFs.[92] Consistent with USEPA recommendations,[4] many regulatory authorities have adopted AFs of 0.03 for soil gas to indoor air and 0.001 for groundwater to indoor air, which are relatively conservative.[4,16] In 2018, 13 of 14 U.S. state environmental agencies with groundwater to indoor air attenuation factors recommended a value of 0.001 for residences; for shallow soil gas to indoor air, 11 of 23 agencies recommend a value of 0.03 and only 4 recommended a value outside a range of 0.02 to 0.1.[16]

Researchers have identified a number of limitations with the AF approach used to calculate subsurface screening concentrations. First, when background VOC sources contribute to the VOC concentration in indoor air, the empirical attenuation factor can be biased high (i.e., underestimate true attenuation).[93−95] If this bias is not adequately controlled when analyzing large empirical AF data sets, then the resulting upper-bound values used for screening AFs will also be biased high.[96] Second, the individual empirical AFs included in large data sets are typically based on a single indoor air and a single subsurface sample. These single measurement empirical AFs exhibit high variability that results in overconservative upper-bound screening;[95,97−100] empirical AFs using spatially and temporally averaged VOC concentrations would be more representative of long-term vapor attenuation. Third, empirical AFs measured at single-family residences are not representative of attenuation for other types of buildings.[101] Finally, screening AFs do not account for other site-specific factors that can affect VOC attenuation such as biodegradation (see section 2.2.1) or fine-grained soil layers (see section 2.2.3). Data gaps associated with the development of refined screening AFs are discussed in section 6.

3.2. Distance-Based Screening. Distance-based screening is generally applied based on the lateral or vertical distance between the edge of the subsurface VOC source and the bottom of the building foundation.[1] If the building is closer to the source

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Table 1. Innovative Vapor Intrusion Investigation Technologies

	principle of technology	functions in VI investigation	advantages	limitations	known field studies
building pressure cycling (BPC)	manipulate indoor−outdoor pressure conditions to either induce or suppress VI; measure changes in indoor air VOC concentration or mass flux/discharge into buildings under positive or negative indoor air pressure[117−120]	(1) distinguish between VI and indoor/outdoor sources of VOCs	(1) can be completed within 1−2 days or less	(1) difficult to apply in large/tall/leaky buildings	residences,[118,121−123] industrial buildings,[36,124,125] offices[123]
		(2) assess VI potential under near worst-case scenario	(2) do not need to collect disruptive subslab soil gas sample	(2) may induce vapor intrusion that would not occur under normal building operation	
		(3) provide evidence of preferential pathway[79]	(3) less expensive than multiple rounds of conventional samplings		
portable GC-MS/GC	portable GC-MS/GC have much smaller size and energy consumption, thus can be used in field; portable instruments are used to do an area-by-area screening followed by more focused sampling in the areas with high VOC concentrations[15,124,126]	(1) identify indoor background sources	(1) real-time on-site analysis with rapid iteration of sample collection and results interpretation	(1) some portable instruments have poor reliability and/or are difficult to use[129]	residences,[126,130−132] industrial buildings,[124] warehouses,[124] vehicle maintenance buildings[124]
		(2) identify vapor entry points	(2) fast[128]	(2) some instruments may have lower sensitivity than bench instruments	
		(3) allow for rapid source identification and mitigation[127]	(3) do not need to collect subslab soil gas sample	(3) requires higher level of operator training compared to conventional investigation methods	
		(4) help to select indoor air sampling locations of sorbent or canister methods[117]			
passive sampling	passive samplers are deployed for a certain period (typically days to weeks) and collect VOCs at a constant uptake rate; the total mass of VOCs trapped in the sorbent can be extracted and analyzed. average concentrations of VOCs can be calculated based on total mass of trapped VOCs, uptake rate, and sampling period[133]	(1) long-term monitoring of indoor air[134] and soil gas[134−138]	(1) can be used for long-term sampling (weeks) and provide average concentrations that reduce the confounding effect of short-term temporal variability	(1) need to match sorbent to target VOCs.; may need additional QA/QC to verify adequate analyte retention and recovery	residences,[134] dry cleaner sites,[138,140] refineries[139]
		(2) delineate the distribution of subsurface contamination[139−141]	(2) can be less expensive than active sampling	(2) for some passive samplers, environmental conditions (temperature, humidity, and deployment time) may have modest effects on sampler uptake rates	
		(3) sewer gas monitoring[82]	(3) easy to deploy and transport		
compound-specific isotope analysis (CSIA)	VOCs from VI and background sources may have different isotope ratios which can be used for source identification	(1) distinguish between VI and indoor sources of VOCs	(1) samples can be collected using established methods (e.g., USEPA TO-17 and passive sampling[142])	(1) not helpful at sites where subsurface sources and indoor sources have similar isotope ratios	residences,[91] industrial buildings[143]
			(2) analysis is commercially available	(2) target VOCs must be identified and quantified to design csia sampling and analytical parameters	
				(3) incorrect sample collection or storage may result in isotope fractionation that could compromise results	
chemical fingerprinting	the chemical composition or compound ratios (fingerprints) of indoor air, soil gas and subslab soil gas, and outdoor air can be characterized; comparison of the chemical fingerprints of indoor air, soil gas, and outdoor air can be used for source differentiation[144,145]	(1) distinguish between VI and indoor/outdoor sources of VOCs	(1) fast	(1) detailed chemical fingerprinting is mainly applicable to petroleum VOCs; it may also be applicable to sites with mixed cVOC wastes	schools,[146] strip malls,[146] business/residential areas[146]

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Table 1. continued

	principle of technology	functions in VI investigation	advantages	limitations	known field studies
		(2) provide more source signature information and improve understanding of the characteristics of subsurface sources	(2) cost-effective	(2) fingerprinting is expected to be qualitative in providing "yes" or "no" to source identification	
radon (natural tracer) test	radon is a naturally occurring compound in soil and soil gas and can serve as a tracer for evaluating VI potential since indoor and outdoor background sources have little contribution to the indoor radon concentrations; the subslab-indoor attenuation factor can be calculated by measuring radon concentration in subslab soil gas and indoor air	(1) measure subslab-indoor attenuation factor[147]	(1) radon measurements are fast and inexpensive	(1) the spatial distribution of radon in the subslab soil gas may be different to that of VOCs leading to differences in subslab to indoor air attenuation factors	residences,[121,147] small office buildings,[147] duplex residences[149]
		(2) measure soil gas entry rate[147]	(2) radon is presence in detectable level (240−2400 PCI/L) in almost all soils	(2) not applicable to sites where VI impacts are attributable to preferential pathways	
		(3) evaluate temporal variability in soil gas entry rate[148]	(3) background contribution from outdoor sources is negligible at most sites		
anthropogenic tracer test	anthropogenic compounds such as sulfur hexafluoride (SF_6), perfluorocarbon tracers (PFTS), helium (He), neon (Ne), and nitrogen (N_2) can be introduced into indoor air, sewers or other subsurface utilities, or soil gas to explore gas movement	(1) measure indoor air exchange rate[150,151]	(1) multiple tracers can be used during a single field sampling event to evaluate multiple potential migration pathways	(1) at high concentrations, density effects may influence transport by advection	residences,[151,152,155] sewer preferential pathways[78,80,122]
		(2) measure vapor entry rate[152]		(2) migration and attenuation of tracer during short-term tracer test may not be representative of typical or longer-term VOC behavior	
		(3) assess preferential VI pathways[78]		(3) sulfur hexafluoride is a greenhouse gas; use may be restricted	
		(4) explore soil gas movement and flux in the vadose zone[153,154]			
flux chamber	inverted containers are installed on the ground surface or building slab; accumulated VOC concentrations (static chamber) or steady-state VOC concentrations (dynamic chamber) are measured to calculate flux rate from subsurface sources[156,157]	measure mass flux rate from the subsurface to ground surface, which can be used as supplement to indoor air, soil gas, groundwater and soil concentration in MLE approach	(1) static chambers are simple in structure and easy to deploy. multiple static chambers can be deployed at the same time	(1) not reliable for general evaluations of VI for existing buildings	petrochemical plants,[158] Picatinny arsenal site,[159,160] gas stations,[161] refineries,[161] landfills,[162−164] experimental sites,[165] industrial warehouses[166]
			(2) may be useful for evaluation of potential future VI at currently undeveloped sites	(2) the presence of a building would change surface flux, therefore measurement results from undeveloped land may not be representative of flux into future buildings	
			(3) may be useful to test potential vapor entry points	(3) surface flux may have large temporal and spatial variability, thus multiple time and location sampling may be necessary	
high-frequency continuous online monitoring	automated continuous monitoring system is used to conduct high-frequency monitoring of VOC indoor air concentrations from multiple sampling locations[122,155,167−169]	(1) obtain high temporal resolution data of VOC indoor air concentrations to document the problem of temporal variability	(1) obtain a large amount of data automatically	(1) less cost-effective for short-term applications	industrial buildings,[167−169] residences[121,122,155]
		(2) obtain in situ VOC indoor air concentrations from multiple locations within one building or from multiple buildings to document the problem of spatial variability[167]	(2) potentially cost-effective method to characterize the temporal	(2) impractical for long-term monitoring across larger numbers of buildings[170]	

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Table 1. continued

	principle of technology	functions in VI investigation	advantages	limitations	known field studies
			changes in indoor air concentrations in a single building over extended periods of time	(3) essential to verify the calibration	
high purge volume subslab sampling	a high-flow vacuum blower is used to purge the subslab soil gas sampling port at a high flow rate (100−1000 L/Min) to collect integrated sample over a large volume to provide a spatially averaged subslab soil gas concentration;[171] mathematical analysis can be used to calculate a building-specific attenuation factor[172]	(1) provide an integrated measurement of VOC subslab concentration	(1) reduce the number of subslab soil gas sampling ports	(1) assumption of radial flow may not be valid for some building foundations	residential buildings,[173] commercial buildings,[173], industrial buildings[171]
		(2) a portable analytical instrument can be used to measure the temporal changes in the VOC_S, O_2 and CO_2 concentrations in purged flow; VOC data can provide some information on the spatial distribution of subslab VOCs; O_2 and CO_2 data can be used to quantify leakage of indoor air across the floor slab and associated dilution of VOC concentrations in purged flow	(2) minimize the effect of spatial variability and the risk of failing to identify the area with high voc concentrations	(2) high flow rate sampling may result in dilution of subslab soil gas by ambient air drawn from the edge of the foundation and/or indoor air drawn down through slab	
		(3) mathematical models can be used to provide information on subslab permeability and slab leakage based on flow/vacuum measurements	(3) quantify mass loading available from subsurface for comparison to mass loading needed to sustain indoor air concentrations of concern	(3) it is not applicable for buildings with wet basements, crawl spaces, foundations directly on bedrock and foundations with complex features such as multiple superimposed floor slabs[171]	
		(4) subslab tracer testing can be added to quantify induced velocities below the slab	(4) quantify the rate of air leakage through the floor to assess whether floor sealing would be beneficial		
			(5) provide design parameters for a full-scale remedial system (if needed)		

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than the **screening distance**, then further evaluation of VI is recommended.[4] A distance of 100 feet (30 m) has commonly been used for both lateral and vertical distance-based screening since the late 1990s−early 2000s.[3,4] This screening distance is supported by modeling[102] and observations at other VI sites.[103] The approach does not account for VOC migration through preferential pathways, which may occur over greater distances.

In recent years, shorter screening distances for petroleum hydrocarbons have been widely adopted based on the recognition that petroleum VOCs rapidly biodegrade within the vadose zone.[38,46,104] For higher strength (LNAPL) sources, vertical separation distances of 15 to 18 feet have been recommended, while distances of 5 to 6 feet have been recommended for lower strength (dissolved-phase) sources.[5,105,106] While large data sets were used to develop **petroleum screening distances**, these data sets focused on underground storage tank sites with gasoline releases,[5,105,107] including gasoline with up to 10% v/v ethanol[17,18] or 15% v/v methyl *tert*-butyl ether.[108] Less data were available, and there is accordingly higher uncertainty, for screening distances associated with other fuel types[52,108] and other site types such as industrial facilities (e.g., refinery). Vertical screening distances may not be applicable for sites with very large buildings where the large foundation footprint can limit the availability of oxygen in the vadose zone.[5,36,109] In addition, published studies focus on key risk drivers for petroleum (e.g., benzene). Less information is available on the VI risks associated with total petroleum hydrocarbons (TPH),[110] in part, because of uncertainties in quantifying vapor concentrations in indoor air resulting from background sources and challenges in defining VI risk-based screening levels for complex TPH mixtures with varying composition, toxicity, and fate and transport. The VI screening distances recommended by ITRC (2014) and US EPA (2015) have, nevertheless, been validated for certain TPH carbon ranges (e.g., C5−C8 aliphatics, C9−C12 aliphatics, and C9−C10 aromatics) with published toxicity factors.[111]

3.3. Soil Type and Other Site Factors. Although initial pathway screening most commonly relies only on consideration of concentration and distance, attempts have been made to include other site factors such as soil type. Early USEPA guidance provided a matrix of screening concentrations for groundwater values based on site-specific soil type and vertical distance.[3] However, the USEPA empirical AF data set did not show clear relationships between AFs and either soil type or vertical distance[92] and these site factors were not included for initial screening in more recent USEPA guidance.[4] The absence of an observed relationship between soil type and AF may be due to the very large overall site-to-site variation in empirical AFs. In other words, building-specific variations in VOC attenuation may overwhelm the effect of soil type. A more focused field study demonstrated a clear relationship between soil type and VOC attenuation from groundwater to soil gas with higher attenuation in fine-grained soils.[71] However, currently, most VI guidance documents do not account for soil type during initial pathway screening.

The broad range of AFs observed across VI sites (more than 3 orders of magnitude variation) indicates that site factors beyond VOC concentration and distance are critical in the occurrence of VI. Because of this, regulatory screening levels are usually set at very protective levels and initial pathway screening retains the VI pathway at a large number of sites where the actual risk of VI could be very low. A better understanding of the effects of soil type and other site factors on VOC attenuation and more rigorous soil vapor sampling protocols are would facilitate the development of more robust initial screening criteria for the VI pathway.

4. VAPOR INTRUSION INVESTIGATION TOOLS

Current VI investigation and risk assessment practices defined in regulatory and consensus-based guidance documents rely on a **multiple-lines-of-evidence (MLE)** approach which most often involves monitoring of different environmental media (section 4.1) and can be supplemented by innovative investigation (section 4.2), VI modeling (section 4.3), and nonconventional lines of evidence (Text S3).[4]

4.1. Traditional Concentration-Based Investigation Method. In practice, VI risk assessment decisions are made primarily based on VOC concentrations in groundwater, soil gas, and indoor air.[1] Although the sampling and analysis methods for these media are relatively mature, they still face problems such as sample container contamination[112,113] and several other challenges (see section 5). Note that soil sampling, which currently provides the most important evidence for site risk assessment and decision making in China,[1,113,114] is generally not recommended for VI assessment based on USA's experiences,[113,114] since no studies reported meaningful correlations between paired VOC concentrations in soil and soil gas and volatilization loss of VOCs is difficult to avoid during soil sampling.[113,115,116]

4.2. Innovative Investigation Techniques. In recent years, a number of innovative VI investigation techniques have been developed (Table 1). While these techniques can help clarify the VI conceptual model and supplement the concentration-based investigation,[15] the use of these tools is not common due, in part, to two reasons. First, practitioners and regulators may not be very familiar with these innovative methods. Second, most of the innovative techniques are not included in regulatory guidelines. Training practitioners and regulators and getting standard procedures written into regulatory guidance are critical for the wide acceptance of these techniques in the future.

4.3. Mathematical Models. Vapor intrusion models simulate vapor migration through the vadose zone and entry into the building and can be used to estimate indoor air concentration from subsurface contamination. VI modeling is an active research area, and a large number of VI models with different model assumptions, governing equations, boundary conditions, model outputs and functions have been published.[22,28,44,45,76,106,120,172,174−203] Several review papers on VI models have been published;[6,10−12,14,204] therefore, this section focuses on the limitations, knowledge gaps, and appropriate applications of VI models that previous review papers do not address.

There are still debates on the accuracy and reliability of VI models. No VI model has been strictly validated by field data, thus limiting the utility of use of models for VI risk assessment.[1,14,114] Although only a few studies have compared VI model predictions against site data, these studies have generally found orders-of-magnitude deviation between model-predicted and measured indoor air concentrations[11,37,205−208] despite recent model show improved performance.[30] While most of these studies have found that VI models generally overpredict indoor air concentration, under-predictions may also occur in some cases.[205,209] An evaluation of five VI models using data from four petroleum sites found that models that include advective transport through the foundation generally

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overpredicted VI. However, models accounting only for diffusive transport could yield overpredictions or under-predictions.[207] An evaluation of seven VI models using data from two petroleum sites and one cVOC site found that all of the models had a tendency to overpredictions of VI but that the most accurate models could also under-predict VI in some cases.[205]

A mathematical model is a simplification of reality and hence will not reflect all of reality. Errors and inaccuracy associated with VI modeling come from four main sources.[1] **(1) Incorrect conceptual model**. For example, most VI models are based on the conventional VI pathway (section 2.1). Using these models for sites impacted by preferential pathways could result in significant errors. **(2) Incomplete model**. For example, many VI models account for vapor entry into buildings only though a gap in the foundation around the perimeter of building and do not account for other important building characteristics such as fluctuating building pressure. Such models may predict unrealistic distributions of VOCs in soil gas below the building and cannot be used to evaluate temporal variations in VI. **(3) Inaccurate mathematical approximations**. For example, the Millington and Quirk equation,[69] which is used by many VI models to calculate the effective diffusion coefficient of VOCs in the vadose zone, is based on empirical relationships that may not be representative of the true value.[210] **(4) Inaccurate model input parameters**. Most of VI models require a large number of input parameters (e.g., > 20 in J&E model), some of the input values are very difficult (if not impossible) to obtain from target site. Sensitivity and uncertainty analysis show that even small changes in some input parameters may lead to several orders of magnitude of variation in predicted indoor air concentration.[33,211−217] Unreasonable input values result in unreasonable outputs. Further, improper use of models or improper interpretation of modeling results would lead to misleading conclusions. For example, improper use of the J&E model has mistakenly screened out more than 300 homes at the Redfield site of US based on simulated indoor air concentrations up to 200 times lower than the monitoring data.[211] In contrast, using model parameters based on field-derived data indicated agreement of the J&E model to within an order-of-magnitude of the data,[218] a reasonable accuracy for a screening-level model. The difference indicates both the importance in selection of appropriate model parameters[214] and the usefulness of sensitivity evaluations in model applications.

"*All models are wrong, but some are useful*".[219] Although VI models are not perfect, they can be useful in some situations.[1] Conservative models can be used as part of the VI site screening process. Models can provide theoretical illustrations and predictions of fate and transport processes of VI pathway, complimenting laboratory and field research and improving mechanistic understandings. Modeling results can also be used as one line of evidence as part of the MLE approach for VI assessment.[4,5] However, they should not be used as stand-alone conclusive evidence for VI assessment and decision making as was common practice in the US prior to the early 2000s and now elsewhere, such as in China.[1,114] Rigorous model validation using independent field investigation data sets (i.e., data sets not used in model development) is important for an improved understanding of the accuracy and limitations of VI models.

5. CHALLENGES IN VAPOR INTRUSION INVESTIGATION AND DECISION MAKING

VOC concentration data typically constitute the basis for current VI risk assessment and decision-making practices. However, interpretation of indoor air and soil gas monitoring data is usually complicated by several challenges including spatial and temporal variability in concentration data (section 5.1) and background sources contributing to indoor air VOCs (section 5.2).

5.1. Spatial and Temporal Variability in Monitoring Data. *5.1.1. Soil Gas.* There can be large spatial variabilities in soil gas concentrations even beneath small buildings. In a < 200 m^2 duplex house, the chloroform concentrations varied from nondetect to 69 $\mu g/m^3$ among five subslab soil gas sampling locations.[220] In a 15 × 14 m warehouse, the TPH concentrations in subslab (0.15 m bgs) and shallow soil gas (0.6 m bgs) had large spatial variation (<100 to >10 000 mg/m^3) while the variability was smaller for deep soil gas (1.2 m bgs).[221] Similar spatial variabilities of soil gas were reported in other studies.[98,103,222] Factors that contribute to the spatial variability include heterogeneity in geological and hydrogeological conditions, contaminant distribution in the subsurface, building structures, ground covers, and preferential pathways.[103,223,224] These results imply that (1) a few samples (by conventional method) may not be representative of the VOC distribution in subslab and shallow soil gas, (2) exterior soil gas cannot represent the VOC distribution in subslab soil gas at the same depth, and (3) a few samples may be enough to characterize deep (source zone) soil gas.

While spatial variability can be high for soil gas, there is often a lesser degree of temporal variability. At a drycleaner site, the PCE concentration in subslab soil gas varied by ∼10-fold over 1.5 years.[103] Long-term (seasonal) and short-term (daily) variability of subslab and exterior soil gas were also reported at other sites.[98,225]

5.1.2. Indoor Air. In contrast to soil gas, spatial variability in indoor air is typically low. Indoor air samples are typically collected in occupied spaces to evaluate risk.[4] In such areas, the air is generally well mixed, resulting in relatively consistent concentrations in the structure. This is particularly true in the absence of localized VOC emission sources or in buildings without separate air handling zones.[226] Higher indoor air VOC concentrations within a specific area such as the basement, a closet, bathroom, or garage usually indicate the presence of an indoor source instead of subsurface VI. Portable GC-MS/GC measurements have shown 100-fold concentration differences when localized sources were present.[124,126,130] These results suggest that (1) for large buildings, separate samples should be collected from different air handling zones and (2) field screening with portable instruments may be used to supplement bulk air samples, to identify specific sources and distinguish between indoor sources and vapor intrusion.

There can be large temporal variabilities in indoor air concentrations over the time scale from hours to months. In cases with documented VI, indoor concentrations can vary seasonally with higher concentrations commonly detected in the winter heating season.[149,155] In buildings impacted by conventional VI, indoor air concentrations (by 24-h sampling) commonly vary by <10-fold.[84,103] For instance, in separate studies of 45 residences and 3 commercial, industrial, and residential buildings, indoor air concentrations typically varied by less than 3-fold.[103] However, there appears to be a greater

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degree of variability within buildings impacted by sewer VI. For example, 1000-fold (<0.01−10 $\mu g/m^3$) seasonal variation of indoor air TCE was observed over 2.5 years as a result of VOC flux through a land drain line.[30,121,122,155] In two other sewer VI cases, >100-fold variations in indoor air concentrations were reported over one year.[81,149] The apparent difference between conventional and sewer VI is consistent with (1) VOC concentrations in sewers exhibiting high variability and (2) the expectation that pipe flow into buildings is more sensitive to a variety of factors than soil gas entry into buildings.

Building differential pressure is likely a key parameter for temporal variations in VI. Building differential pressure would affect pipe flow into buildings and could drive other vapor entry mechanisms.[122,227] For instance, daily variations in TCE indoor air concentrations (<10−400 $\mu g/m^3$) have been reported by high-frequency continuous monitoring in a large warehouse, and has been attributed to indoor-subsurface pressure differentials (see Table 1).[168] Many other factors such as temporal variability of soil moisture,[223,228] soil temperature,[223,228] building ventilation (combustion applications, open windows, and HVAC),[27,227] VOC mass storage in the groundwater and vadose zone,[229] meteorological conditions (e.g., barometric pressure, wind, and temperature),[230] and groundwater−water table fluctuation[64] may also contribute to the temporal variability of indoor air concentrations.

A variety of investigation methods have been developed to control for temporal variability in indoor air (Table 1). Common practice includes 24 and 8 h sampling periods for residential and industrial buildings, respectively. However, longer duration sampling using passive sorbent samplers[231,232] or capillary flow controllers for canisters[233] reduces the impact of temporal variability by averaging over a longer time period.[231,232] Another technique is building pressure cycling which can be used to "turn on" or "turn off" VI, thereby reducing concerns with false negatives and false positives.[118,124,234] High purge volume sampling has been developed to alleviate the spatial variability of subslab soil gas. For buildings with a high permeability layer (e.g., gravel) below the foundation, high purge volume sampling can be used to provide a spatially averaged subslab concentration over a large spatial area below the foundation from one or a few sample points.[171,173]

5.2. Indoor Air Background Concentrations. Interpretation of indoor air data can be confounded by the background contribution of VOCs from indoor and outdoor VOC sources that are unrelated to VI.[2,4] Common **indoor background sources** include consumer products, building materials, combustion processes (e.g., smoking, cooking, and heating), and occupant activities (e.g., cleaning, car repair, and decoration).[235] Outdoor air can also contribute to indoor air contamination.[146] A wide variety of consumer products have been found to contain BTEX constituents[236] or chlorinated VOCs.[126] **Emissions testing** has shown that VOCs are released from both unopened and opened/partially used consumer products with emissions rates as high as 24 $\mu g/min$ reported for a partially used product containing PCE.[237,238] While some consumer products are clearly labeled as containing specific VOCs, other products do not identify the presence of VOCs that may be present as impurities or are considered inert ingredients. For example, self-defense pepper sprays advertised as "non-flammable" commonly use TCE as the carrier solvent without listing its presence on the product label. In addition to consumer products, chemical reactions between bleach cleaners and organic matter can also result in detectable levels of chlorinated VOCs in indoor air.[239]

Studies have explored the typical range and variation trends of indoor background VOC concentrations in different countries/areas including North America,[235,240−244] China,[245−248] Europe,[249−251] and others.[248,252−254] The background concentration of the same VOC varied considerably among different areas/countries.[248,251,255] This can be attributed to differences in the geographic settings, climatic conditions, building structures and materials, indoor air exchange rates, living habit, household products, and outdoor air concentrations. Compilations of North American data reveal several interesting phenomena:[235,242] (1) typical indoor background concentrations are log-normally distributed; (2) the variations between the 25th to the 95th percentile values of most VOCs are >10-fold (typical sampling period are between 12 and 24 h; longer sampling period would result in lower variations); (3) for a number of common VOCs such as benzene, carbon tetrachloride, chloroform, and PCE, the upper end of the observed range for background indoor air concentrations typically exceeds USEPA's regional screening levels.[256] For many individual VOCs, the observed range of indoor air concentrations has generally declined in recent years likely due to concerns regarding the toxicity of individual VOCs resulting in the general move toward the development of consumer products containing lower total VOC concentrations.[241,257] However, indoor air concentrations of at least one individual chlorinated VOC (1,2-dichloroethane) has been observed to increase over time apparently due to changes in the manufacturing of molded plastics.[238,243]

To reduce the impact of indoor sources, regulatory guidance typically recommends identifying possible indoor sources by occupant questionnaires and indoor surveys and removing them prior to testing of indoor air for the evaluation of vapor intrusion.[4] However, in many cases, it is not possible to identify all sources though visual inspection. In other cases, removal of indoor sources is not practical.[4] In several cases where background sources were not properly identified or considered during initial testing, VOC detections in indoor air were initially attributed to VI; indoor sources were identified only through subsequent testing.[146,238,243,258] If the background concentration is mistakenly attributed to VI, it may result in unnecessary and ineffective site investigation and mitigation. Therefore, it is necessary to assess the contribution of background sources to indoor air contamination.

Innovative site investigation techniques can be used to distinguish the background sources from VI (Table 1). Portable GC-MS or GC has been successfully used for identifying potential indoor background sources or vapor entry points.[124,126,128,130,131] Another applicable method is building pressure cycling (BPC) which involves manipulation of indoor-outdoor pressure conditions to either induce or suppress VI.[118,121,234] Under positive indoor pressure, subsurface VI is minimized and indoor air sampling can be used to characterize the background sources of VI.[118,119] A combination of portable GC-MS and BPC has been successfully used to identify indoor background sources at several sites.[124,126,259] CSIA has been used to distinguish between background sources and VI.[91,143,260] Isotope signatures of VOCs may change over time due to fractionation effects associated with biodegradation or physical processes (e.g., diffusion, volatilization, sorption, and dissolution).[261] The differences in isotope signatures between subsurface sources and indoor-relevant products can be used to

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identify the origin of indoor VOCs.[91,143,260] CSIA analysis needs a relatively large amount of analyte (e.g., > 1 ng of C), but VOC concentrations in indoor air are relatively low ($\sim\mu g/m^3$). Adsorbent[142,262] and solvent-based[263,264] methods have been developed to concentrate air samples, allowing the use of CSIA methods for VI investigation.

6. KEY TOPICS FOR FUTURE RESEARCH

Although there have been significant advances in the understanding of VI over the past 20 years, knowledge gaps still exist. These gaps, summarized below, are areas for potential future research.

Gap 1: Initial VI Pathway Screening. Initial screening of the VI pathway typically focuses on VOC concentrations in groundwater and soil gas and separation distance between the subsurface source and buildings. This screening does not account for the site-specific role of barriers (e.g., clean water lens, high moisture soils, biodegradation, building foundation, and building pressure) in preventing VI at many sites. An improved understanding of the specific site features that reliably prevent VI and adequate tools to identify these features early in the site investigation process have the potential to improve initial VI pathway screening, particularly for nonpetroleum VOCs.

Gap 2: Preferential Pathways. The importance of sewers and utility tunnels as preferential pathways for VOC migration into buildings has received increased focus in recent years. The current understanding of transport processes within preferential pathways is limited compared to conventional VI. Areas where an improved understanding is needed include: transport processes inside pipes versus through backfill, transport processes in the liquid phase versus vapor phase, spatial and temporal variability within sewer lines and utility tunnels, and identification of reliable barriers to VOC migration within sewer lines and from sewer lines into buildings.

Gap 3: Conceptual Model for VI into Buildings Other than Single-Family Residences. Building structures and characteristics significantly affect the susceptibility of buildings to VI.[1] However, most accumulated knowledge on VI has been obtained from single-family residential houses that are common in the US and Canada. For example, 85% of the measurements in the USEPA data set used to establish upper-bound attenuation factors are from single family residences.[92] In addition, the two well-documented VI research sites are a single family residence[121,122,155,229] and a residential duplex.[149,220,265,266] The current VI conceptual models, site screening criteria (e.g., screening distances, screening concentrations, and attenuation factors), and VI mathematical models have been developed almost exclusively based on scenarios involving single-family residences. Although testing of other building types such as high-rise apartments, shopping malls, office buildings, industrial buildings, and specialty buildings (school, hospital, transport station, and religions) is commonly conducted during VI investigations, test results have not been compiled into a large public database and the effect of these buildings on VI processes and pathways has not been defined (Figure S2).

Gap 4: VI into Underground Structures. The majority of VI research to date has focused on above ground structures, with less emphasis on underground or submerged structures.[1] These underground structures are common in the urban cores of large cities, particularly in Asian and European countries. In these urban cores, underground structures form the backbone of the infrastructure of the city (e.g., underground parking garage, subway stations, and pedestrian and traffic tunnels) and these underground structures are often located in close proximity to active or historical industrial sites with subsurface releases. For cities near coastal areas (e.g., New York, Shanghai, Hong Kong, Singapore, and Tokyo), the groundwater table is very shallow (1−3 m), and as a result, many of the underground structures extend below the groundwater table.[1] While these underground structures typically include engineered barriers or hydraulic control to minimize groundwater infiltration, the effectiveness of these controls to prevent vapor intrusion has not been verified. The close proximity between subsurface VOC sources and underground structures may enhance the potential for VI, while the often high ventilation rates and relatively short average occupancy duration may limit the magnitude of exposure. Many underground structures are equipped with dedicated ventilation systems which may, in certain cases, serve as a long-term, sustainable engineering controls. Additional research is needed to understand to overall VI risk associated with underground structures (Figure S2).

Gap 5: Technology Transfer. Much of the improved understanding and innovative investigation tools are not routinely utilized for VI investigations and decision-making. Research is needed to identify the most effective methods to transfer new knowledge to practitioners (e.g., scientific publications, classroom training, online training, social media). Regulatory and consensus-based guidance documents need to be updated regularly to reflect new knowledge. In addition, the evaluation and decision-making frameworks should be flexible enough to support the adoption of innovative approaches as they are developed and validated.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c00225.

> Wind effects, stack effects, and mechanical ventilation, indoor air exchange rate, nonconventional lines of evidence for evaluation of vapor intrusion, vapor intrusion investigation strategies, key vapor intrusion guidance documents published by different countries, vapor intrusion guidance documents published by the different institutes and states of US, driving force of vapor entry by advection is caused by a combination wind effect, stack effect, and mechanical ventilation, critical knowledge gaps, and two VI investigation approaches after initial pathway screening (PDF)

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Notes

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■ ABBREVIATIONS

VI	vapor intrusion
VOCs	volatile organic compounds
US	United States
USEPA	United States Environmental Protection Agency
AER	indoor air exchange rate
pVOCs	petroleum VOCs
cVOCs	chlorinated VOCs
VC	vinyl chloride
DCE	dichloroethene
TCE	trichloroethylene
PCE	perchloroethylene
AF	attenuation factor
J&E model	Johnson and Ettinger model
sewer VI	sewer vapor intrusion
CSIA	compound-specific stable isotope analysis
NAPL	nonaqueous phase liquid
MLE	multiple-lines-of-evidence
BPC	building pressure cycling
GC	gas chromatography
GC-MS	gas chromatography−mass spectrometry
QA/QC	quality assurance/quality control
TPH	total petroleum hydrocarbons
HVAC	heating, ventilation, and air conditioning
BTEXs	benzene, toluene, ethylbenzene, and xylenes

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