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Air Exchange Rates and Alternatuve Vapor Entry Pathways to Inform Vapor Intrusion Exposure Risk Assessments

Rivka Reichman
University of Kentucky

Mohammadyousef Roghani
University of Kentucky, m.roghani@uky.edu

Evan J. Willett
University of Kentucky, evan.willett@uky.edu

Elham Shirazi
University of Kentucky, elham.shirazi@uky.edu

Kelly G. Pennell
University of Kentucky, kellypennell@uky.edu

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Mini Review

Rivka Reichman, Mohammadyousef Roghani, Evan J. Willett, Elham Shirazi
and Kelly G. Pennell*

Air exchange rates and alternative vapor entry pathways to inform vapor intrusion exposure risk assessments

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Abstract: Vapor intrusion (VI) is a term used to describe indoor air (IA) contamination that occurs due to the migration of chemical vapors in the soil and groundwater. The overall vapor transport process depends on several factors such as contaminant source characteristics, subsurface conditions, building characteristics, and general site conditions. However, the classic VI conceptual model does not adequately account for the physics of airflow around and inside a building and does not account for chemical emissions from alternative "preferential" pathways (e.g. sewers and other utility connections) into IA spaces. This mini-review provides information about recent research related to building air exchange rates (AERs) and alternative pathways to improve the accuracy of VI exposure risk assessment practices. First, results from a recently published AER study for residential homes across the United States (US) are presented and compared to AERs recommended by the US Environmental Protection Agency (USEPA). The comparison shows considerable differences in AERs when season, location, building age, and other factors are considered. These differences could directly impact VI assessments by influencing IA concentration measurements. Second, a conceptual model for sewer gas entry into buildings is presented and a summary of published field studies is reported. The results of the field studies suggest that alternative pathways for vapors to enter indoor spaces warrant consideration. Ultimately, the information presented in this mini-review can be incorporated into a multiple-lines-of-evidence approach for assessing site-specific VI exposure risks.

Keywords: hazardous waste; indoor air; vapor intrusion; volatile organic compounds.

Introduction

There are many sources of indoor air (IA) pollution, but one that is too often overlooked is the transport of subsurface vapors into IA spaces [i.e. vapor intrusion (VI)]. VI is the process by which chemicals from hazardous waste sites migrate through the soil and ultimately impact the IA quality of buildings. VI is an international environmental health issue that is addressed differently by regulations specific to each country. In general, the United States (US) has provided international direction on VI sampling approaches, while site-specific risk assessment procedures have varied from country to country (1). In 2015, the US Environmental Protection Agency (USEPA) released its highly-anticipated "finalized" VI guidance document, which is described as a flexible framework to inform VI exposure risk assessments (2). In the many years between VI being widely recognized as an environmental health issue (3) and USEPA's finalized VI guidance (4), large unexplained temporal and spatial variations in IA quality data were observed at VI sites [e.g. (5, 6)]. Many scientifically advanced concepts have been noted as possible sources of spatial and temporal variability in VI field data (4). This article reviews two topics of growing interest within the VI community: the effect of above-ground processes, specifically building air exchange rates (AERs), and the role of alternative "preferential" pathways that can increase VI exposure risks.

Conceptualizing VI and considering the role of AER

Vapor transport in the soil is governed by vapor diffusion and is affected by the properties of contaminant and the

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***Corresponding author: Kelly G. Pennell,** Department of Civil Engineering, College of Engineering, University of Kentucky, Lexington, KY, USA, E-mail: kellypennell@uky.edu
Rivka Reichman, Mohammadyousef Roghani, Evan J. Willett and Elham Shirazi: Department of Civil Engineering, College of Engineering, University of Kentucky, Lexington, KY, USA

soil. Vapor entry into the building is assumed to occur by the combination of diffusion and convective transport mechanisms. The convective transport is driven by the pressure difference between the inside of the building and the outside of the building. This pressure difference, known as the driving force for vapor entry, is caused by a combination of the stack effect (temperature difference between the outside and inside of the building), wind effects, and building ventilation processes. Once soil vapors enter the building, it undergoes a mixing that is influenced by the AER. Figure 1 provides a conceptual model of the VI process.

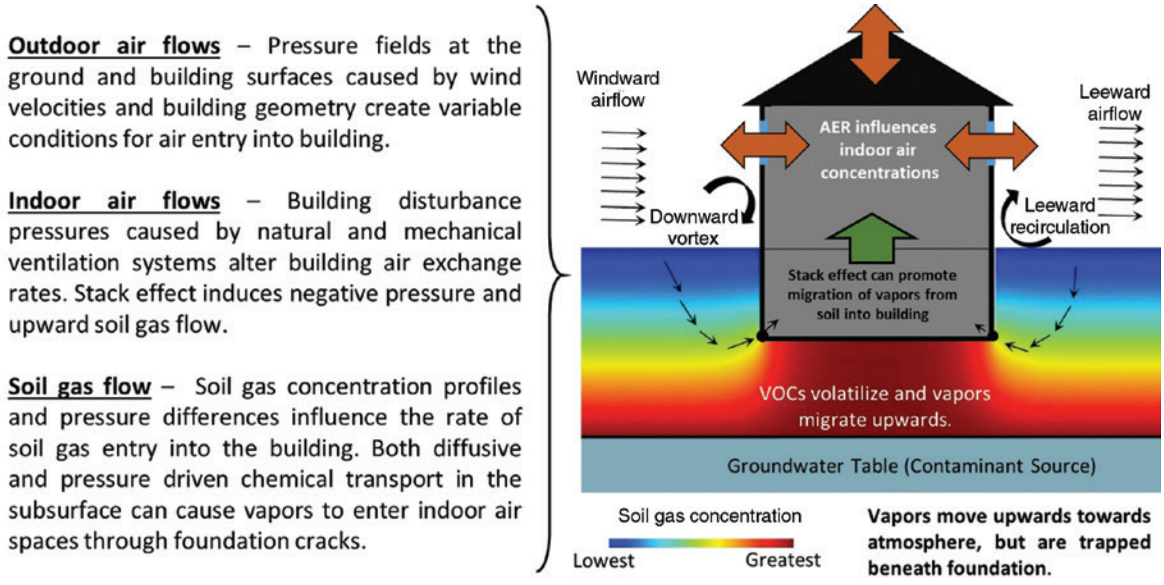
Several VI numerical models have been developed to describe VI processes (7–13). No VI model currently exists to describe all of the processes shown in Figure 1. However, a few VI models (12, 13) have attempted to account for the processes shown in Figure 1 by expanding the work of prior radon intrusion models (14, 15) that incorporate not only the subsurface fate and transport processes, but also above-ground processes that impact VI. More research is needed in this area to investigate the effect of above-ground processes on VI. While research continues, this article aims to summarize existing literature related to AERs and summarizes some key implications for VI.

Building AERs

AER is noted as an important parameter to consider during VI site-specific risk assessments in the USEPA VI finalized guidance (4) and is included in many international VI regulatory risk assessment frameworks (1). AER values cited by regulatory agencies are often used for conservative risk assessment purposes and are qualified as being specific for that intended use; however, there is a need for decision makers conducting VI site assessments to consider the broader range of relevant AER values when interpreting the results of IA measurements. The following subsection summarizes key published literature that is relevant to AERs and serves as a resource for decision makers.

AER is the rate at which the volume air contained within the whole house exchanges with the outdoor air. When the time unit is hours, AER is also called air changes per hour (ACH, 1/h). Air exchange is the sum of two processes: infiltration and ventilation (16). Infiltration refers to uncontrolled outdoor air flow through unintentional openings in the building envelope, that is, leaks. Ventilation includes natural ventilation and mechanical ventilation. Natural ventilation is outdoor airflow through intentional openings such as open windows, and is driven by weather. Mechanical ventilation is airflow induced by powered equipment. A detailed description of infiltration and ventilation is provided in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook (16).

AER distributions are usually expressed using a log-normal distribution (17–20). The key existing datasets for AER distribution are Brookhaven National Laboratory (BNL) (17, 18), Detroit Exposure and Aerosol Research



Outdoor air flows – Pressure fields at the ground and building surfaces caused by wind velocities and building geometry create variable conditions for air entry into building.

Indoor air flows – Building disturbance pressures caused by natural and mechanical ventilation systems alter building air exchange rates. Stack effect induces negative pressure and upward soil gas flow.

Soil gas flow – Soil gas concentration profiles and pressure differences influence the rate of soil gas entry into the building. Both diffusive and pressure driven chemical transport in the subsurface can cause vapors to enter indoor air spaces through foundation cracks.

Figure 1: Conceptual diagram of the vapor intrusion process.

Study (DEARS) (19), Relationships in Indoor, Outdoor, and Personal Air (RIOPA) (19), and Lawrence Berkley National Laboratory (LBNL) (20). These datasets are a collection of various projects at different regions in the US that were collected on the course of two types of programs: human exposure programs and residential energy efficiency (e.g. BNL, DEAR, and RIOPA), and weatherization assistance programs (WAPs) (e.g. LBNL). In human exposure programs, AER is measured using the perfluorocarbon tracer method. WAPs are assessing building leakage or airtightness and the metric used is normalized leakage (NL). AER and NL can be related using a scaling factor (20).

A summary of two key studies that involved residential AER distributions is presented in Table 1. These two studies (18, 19) were selected because the Koontz and Rector (18) study was the basis for the AER values recommended for conservative risk assessment in the USEPA finalized VI guidance (2015). The Isaacs et al. (19) study includes newer data and is not well known within the US VI community. Examining the data of these two studies shows that residential AER values vary over an order of magnitude and are highly dependent on housing characteristics [e.g. age, air conditioning (AC)], weather (e.g. season, temperature), and geographic region.

USEPA recommends using values in the range of 0.18–1.26 1/h for residential AERs. The Koontz and Rector study (18) is based on the BNL dataset collected during the period of 1982–1987. The study by Isaacs et al. (19) is based on more recent datasets (DEAR: 2004–2007; RIOPA: 1999–2001) and reveals that AER values can be as high as 6.1 1/h (Table 1, Detroit).

The implications of AER on IA concentrations are important because the AER acts to dilute IA concentrations. As the AER increases, IA concentrations decrease. Therefore, if an IA sample is collected during a time when the AER is high, then the ability of an IA sample to inform about the potential for VI is limited. If modifications to the building are made such that the AER is substantially altered, then IA concentrations will also be affected. If VI decision makers do not consider how future changes in a specific building's AER may affect IA concentrations, then VI exposure risks may not be accurately assessed.

Table 1: Typical residential AER distribution studies.

Study	AER distribution				Database	Comments
	Category	Value (1/h)				
		10th	50th	90th		
Koontz and Rector (18)	All regions	0.18	0.45	1.26	BNL	USEPA (2015) recommends using values in the range of 0.18–1.26 1/h for residential AERs
	West region	0.20	0.43	1.25		
	Midwest region	0.16	0.35	1.49		
	Northeast region	0.23	0.49	1.33		
	South region	0.16	0.49	1.21		
		5th	50th	95th		
Isaacs et al. (19)	Detroit, MI				DEARS	Cold weather: T ≤ 65°F
	Cold, newer homes	0.38	0.62	1.64		Warm weather: T > 65°F
	Cold, older homes	0.36	1.02	2.94		Newer home: age ≤ 15 years
	Warm, central AC	0.16	0.31	3.57		Older home: age > 15 years
	Warm, no central AC	0.42	1.82	6.10		
	Elizabeth, NJ				RIOPA	
	Cold, newer homes	0.39	0.56	1.03		
	Cold, older homes	0.32	0.76	4.14		
	Warm, central AC	0.11	0.72	1.04		
	Warm, no central AC	0.30	1.04	3.40		
	Houston, TX				RIOPA	
	Cold, newer homes	0.09	0.28	0.69		
	Cold, older homes	0.18	0.66	2.29		
	Warm, central AC	0.13	0.38	1.10		
	Warm, no central AC	0.23	0.56	2.74		
	Los Angeles, CA				RIOPA	
	Cold, newer homes	0.17	0.42	1.32		
	Cold, older homes	0.32	0.80	2.24		
	Warm, central AC	0.26	0.71	2.70		
	Warm, no central AC	0.21	1.45	4.35		

While many of the median values shown in Table 1 do not vary greatly, there are substantial deviations in the values across the entire distributions that can result in more than one order of magnitude variability in IA concentration (21). Consequently, VI decision makers should carefully consider the implications of AERs when evaluating IA concentrations as part of VI site-specific risk assessments.

VI through alternative "preferential" pathways

As shown in Figure 1, VI has been conceptualized to occur due to vapors entering through cracks in the foundation. Recently, vapor entry through alternative (or preferential) pathways has been gaining attention (22). In this article, we review literature that documents case studies where plumbing systems, land drains, and subsurface utility conduits/lines/trenches have served as transport pathways for volatile organic compounds (VOCs) to migrate. The issue of preferential pathways for VI is related more broadly to aging infrastructure challenges, which are a well-known problem.

In the US, many sewer systems were constructed following World War II and are now approaching the end of their anticipated life. According to the American Society of Civil Engineers, more than $298 billion in capital investments are needed over the next two decades to address deficiencies in the estimated 700,000–800,000 miles of sewer mains in the US (23). Current and future investments on the order of hundreds of billions of dollars are needed to rehabilitate and improve overall operational network efficiency.

Legacy sewer systems have deteriorated due to pipe settlement and corrosion, biological intrusion, and earth subsidence. As deterioration occurs, sewer pipes lose the ability to convey waste streams to wastewater treatment plants without losses. Direct discharge of VOC-contaminated water to sanitary sewers from both industrial and domestic users, contaminated sludge in the sewer system resulting from historical VOC-laden wastewater, contaminated groundwater infiltration into the sewer line due to intersection with damaged sewer pipes, and gas-phase VOC migration from subsurface groundwater and soil gas plumes are potential sources of VOCs in the sewer collection system. Dry cleaning separator water is an example of direct industrial discharge and is a primary source of perchloroethylene (PCE), which is a commonly found VOC in sewers (24).

Figure 2 depicts how VOCs within a sewer system could enter a building through plumbing connections. As shown, VOCs within the wastewater volatilize to the sewer headspace. Gas-phase VOCs can migrate throughout the sewer system and escape at any location where there is not a vapor-tight seal. Vapors may then enter structures located long distances from source zones and contaminate IA. Generally, building leak locations could include cracked waste stacks, dry P-traps, cracked vent stacks, loose fittings, faulty wax ring seals, leaking joints, etc. Jacobs et al. (25) describe the sewer gas-to-IA pathway in more detail.

There are several possible mitigation strategies for decreasing the potential of the sewer system to act as a VI

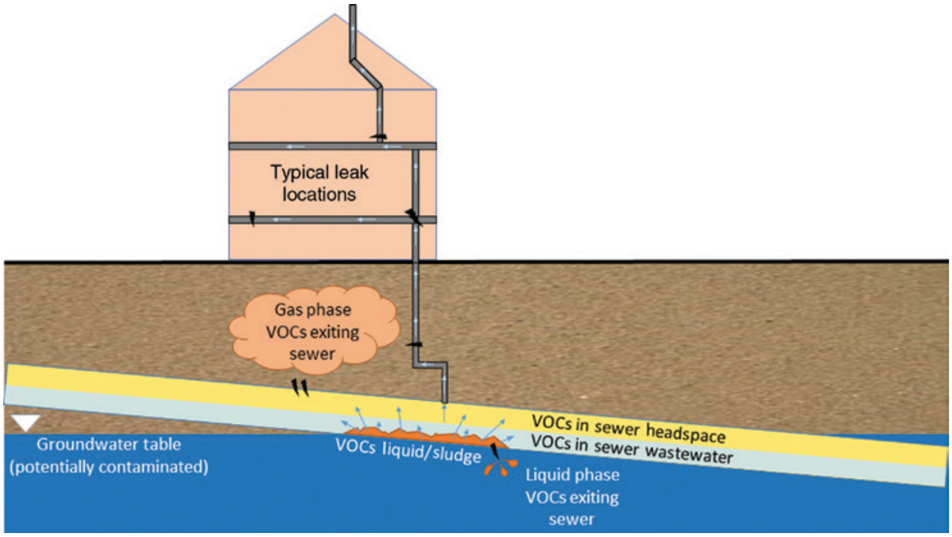


Figure 2: Conceptual model of sewer gas to indoor air pathway.

pathway. These mitigation strategies can be separated into three categories: systemic, domestic, and regulatory. Systemic solutions include (but are not limited to) installing a vapor sorbent in the sewer manhole to capture vapors in the sewer lines before they can enter indoor areas, offgassing contaminated sewer gas to the atmosphere by ventilating sewers, and depressurizing the sewer system. Domestic solutions include replacing degraded toilet wax seals, filling dry P-traps, and joining disconnected pipes and fittings. Regulatory solutions include limiting industrial discharges to the sewer system and groundwater, monitoring sewer liquid and groundwater quality in areas of shallow groundwater with subsurface plumes, and educating the general public about the consequences of disposing hazardous chemicals to sanitary sewers.

Summary of field studies

Several field studies have documented that piping conduits connected to buildings and building foundations can serve as alternative pathways for VOCs to enter IA spaces at VI sites. Below is a summary of some key field studies.

In 1992, Izzo et al. (26) conducted a study in California's Central Valley (US), and it was one of the first reports of a sewer system acting as a preferential pathway for VOC transport. By measuring soil gas VOC levels using glass tubes containing carbon adsorbents placed approximately 25–30 cm below ground surface at various locations, they found elevated VOC concentrations proximal to sewer lines. Nearly two decades later, Distler and Mazierski (27) conducted a VI assessment in Niagara Falls, New York (US), and found evidence of VOC migration through subsurface utilities and sewer lines.

During a VI study in Skuldelev, Denmark, Riis et al. (28) discovered higher-than-expected VOC concentrations in IA at several houses and determined that the elevated IA concentrations were caused by sewer gas intrusion. They conducted a tracer gas study to assess potential pathways for VOCs and found elevated concentrations of PCE and its degradation byproducts, trichloroethylene (TCE) and 1,2-dichloroethene, in the sewer line and plumbing fixtures. The results clearly suggest that the sewer line is the primary VI pathway for the studied properties.

In a residential area in Boston, Massachusetts (US), Pennell et al. (29) observed higher PCE concentrations in IA on the first floor of a home compare to the basement IA of the same home. Follow-up IA and sewer gas sampling demonstrated that the sewer gas from a faulty toilet connection was the primary source of PCE in IA. Similar observations at other field sites were noted by McHugh et al. (30) and Gorder and Dettenmaier (31); however, fewer details are available in the literature.

Guo et al. (32) conducted a long-term VI continuous monitoring study at a house overlying a groundwater plume contaminated by 1,1-dichlorethylene (1,1-DCE), 1,1,1-trichloroethane (1,1,1-TCA), and TCE near Hill Air Force Base in Layton, Utah (US). By applying controlled pressure method testing (which includes whole-house pumping and IA sampling), soil gas sampling, and screening-level emission calculations, the study concluded that subsurface pipe networks, including sewer mains and land drains, have the potential to act as significant alternative VI pathways. Importantly, this field study included a preferential pathway that was an open pipe beneath the foundation. The open pipe terminated under the building foundation and was connected to a sewer that contained elevated levels of VOCs. The purpose of the pipe was presumed to be a foundation drain. As part of the study, researchers installed a valve so that the land drain could be shut and vapors could be prevented from being released (32).

As part of ongoing regulatory activities, USEPA is currently conducting a study at a contaminated groundwater site in Mountain View, California (US). This area is characterized by a 2.5-km-long plume of TCE and its degradation byproducts. Four TCE “hotspot” locations with high groundwater concentrations have been found outside of the regional plume. The hotspots exist in areas of no known TCE sources, but are in proximity to sanitary sewer lines. The sewer line is being investigated as a possible means of transporting TCE to these locations, and the possibility of the sewer transporting gases to IA spaces is also being evaluated. The source of TCE within the sewer line may be attributed to historical industrial discharge into the sanitary sewer system and/or intersection between the contaminated groundwater plume and deteriorated sewer pipes (33).

These studies provide evidence for sewer lines to serve as preferential VI pathways. It is not clear how widely spread this phenomenon exists; however, these observations illustrate that VI decision makers should consider these implications when managing VI exposure risks.

Conclusion

USEPA recommends a multiple-lines-of-evidence approach when making decisions about how to assess VI exposure risks at investigated sites due to the complexities connected with characterizing the VI pathway. This approach uses field data, modeling, and other relevant site information to assess VI exposure risks and allows for considerable flexibility in the types of field data collected. It also allows for flexibility in how the field data is interpreted (4). The information provided in this review about AERs and preferential pathways provides VI decision makers with new information to consider when designing field studies. This new information can be readily incorporated into a multiple-lines-of-evidence approach for assessing VI exposure risks. Ultimately, by increasing awareness of recent research findings among VI decision makers, exposure risks can be more accurately assessed.

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