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# Review of Recent Research on Vapor Intrusion

by

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## **Notice**

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Vapor intrusion is a complex problem where EPA is continuing to develop policies and guidance. This document presents the results of ORD-sponsored research and neither states EPA policy nor requirements for assessment and clean up. The latest policies and requirements should be obtained from the EPA Office of Solid Waste and Emergency Response.

## **Abstract**

This paper reviews current and recent research in the area of vapor intrusion of organic compounds into residential buildings. We begin with a description of the challenges in evaluating the subsurface-to-indoor air pathway. A discussion of the fate and transport mechanisms affecting vapors along this pathway is then presented. Following this discussion is a brief overview of current Federal regulations and proposed guidance concerning vapor intrusion. A review of site studies involving vapor intrusion that have been published in scientific literature is then presented, with a focus on evidence of the extent of the problem. Published approaches to modeling vapor intrusion are presented next, followed by conclusions and ideas about future research needs.

## Foreword

The National Exposure Research Laboratory's Ecosystems Research Division (ERD) in Athens, Georgia, conducts research on organic and inorganic chemicals, greenhouse gas biogeochemical cycles, and land use perturbations that create direct and indirect, chemical and non-chemical stresses, exposures, and potential risks to humans and ecosystems. ERD develops, tests, applies and provides technical support for exposure and ecosystem response models used for assessing and managing risks to humans and ecosystems, within a watershed / regional context.

The Regulatory Support Branch (RSB) conducts problem-driven and applied research, develops technology tools, and provides technical support to customer Program and Regional Offices, States, Municipalities, and Tribes. Models are distributed and supported via the EPA Center for Exposure Assessment Modeling (CEAM) and through access to Internet tools ([www.epa.gov/athens/onsite](http://www.epa.gov/athens/onsite)).

Intrusion of contaminated vapors into buildings ("vapor intrusion") may provide a significant pathway for exposure to hazardous contaminants. Assessment of this problem is difficult, because of limitations of sampling methodologies, contamination in ambient air, internal sources and sinks of contaminants and uncertainty in model application. The information in this report is intended to provide a background for future work that addresses the complexities of this problem.

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## Acronyms and Abbreviations

ACH	Air changes per hour
ANAS	Alameda Naval Air Station
BTEX	Benzene, toluene, ethylbenzene and xylenes
EPA	Environmental Protection Agency
CDOT-MIL	Colorado Department of Transportation Materials Testing Laboratory
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
GW	Ground water
IAQ	Indoor air quality
IMPACT	Integrated Moisture Plus Contaminant Transport Model
LUST	Leaking underground storage tank
MADEP	Massachusetts Department of Environmental Protection
NAPL	Nonaqueous phase liquid
OCHCA	Orange County Health Care Agency
OERR	Office of Emergency and Remedial Response
OSWER	Office of Solid Waste and Emergency Response
RCRA	Resource Conservation and Recovery Act
THC	Total petroleum hydrocarbons
TCE	Trichloroethene
USEPA	United States Environmental Protection Agency
UST	Underground storage tank
VI	Vapor intrusion
VOC	Volatile organic compound

# 1 Introduction

The term “vapor intrusion” (VI) refers to the transport of vapors from volatile organic compounds (VOCs) or other contaminants of interest from the subsurface into buildings. As the average American spends over 21 hours per day indoor and roughly 18 hours indoors for every hour spent outdoors (Olson and Corsi 2002), the potential presence of harmful vapors in buildings is of great importance. VOCs in living spaces can serve as an immediate threat, for instance, explosion, or, more insidiously, as a long-term source for exposures to potential carcinogenic or toxic compounds. The source of organic vapors in the subsurface can come from accidental or intentional releases, leaking landfills or leaking underground and above ground storage tanks. Organic compounds of concern in vapor intrusion are usually divided up into two broad categories: chlorinated solvents and petroleum hydrocarbons. Once organic compounds are introduced into the subsurface, a complex series of fate and transport mechanisms act upon them, potentially moving them away from the source area. Hydrocarbons may be transported beneath residences as a separate phase (NAPL), dissolved in ground water or as a vapor in soil gas. Once these contaminants are present near or beneath buildings, they may move as a vapor through soil gas and into the residence. Vapor intrusion is an area of active research as engineers and scientists grapple with evaluating and predicting human exposure to harmful vapors emanating from the subsurface.

This report reviews current and recent research in the area of vapor intrusion of organic compounds into residential buildings. We begin with a description of the challenges in evaluating the subsurface-to-indoor air pathway. A discussion of the fate

and transport mechanisms affecting vapors along this pathway is then presented. Following this discussion is a brief overview of current Federal regulations and proposed guidance concerning vapor intrusion. A review of site studies involving vapor intrusion that have been published in scientific literature is then presented, with a focus on evidence of the extent of the problem. Published approaches to modeling vapor intrusion are presented next, followed by conclusions and ideas about future research needs.

## **2 Challenges in Evaluating the Vapor Intrusion Pathway**

Several challenging issues exist that make vapor intrusion a particularly difficult pathway to assess. First, while there have been reported cases where organic vapors have been present above the odor threshold in homes, it is not known whether vapor intrusion is a widespread problem, particularly for long-term exposure to low-level concentrations. While caution would require the evaluation of the soil-to-indoor air pathway for all subsurface contamination, there are, in fact, not many cases of proven vapor intrusion documented in the scientific literature. This is particularly true for organic vapors subject to aerobic biodegradation, such as gasoline compounds (petroleum hydrocarbons). Secondly, determining the impact of organic vapor intrusion in residential buildings is not necessarily a straight forward exercise. Indoor air sampling and analysis is a fairly routine procedure, yet the interpretation of the results is often difficult. Many household building supplies and products such as furniture, carpets, textiles, household cleaners, sealants, gules, adhesives, paints, waxes, lubricants, heating systems (i.e. fuels), cooking vapors, and personal care products contain organic compounds identical to common

contaminants in soil or ground water (Hers et al. 2001). The quality of the air outside the home may also be important because some of these contaminants may be present from this source. Therefore, detection of VOCs in indoor air that are also present in the subsurface does not conclusively link the two systems. Additionally, there are household materials that serve as a sink for VOCs from indoor air including wallboard, ceiling tile, carpet, and upholstery. During high-concentration periods, adsorption of VOCs by these materials can reduce peak concentrations. The adsorbed VOCs may become an additional indoor source during periods of reduced indoor air concentration or as a result of changes in temperature or other environmental factors (Hers et al. 2001).

Due to the difficulty in conclusively identifying the soil-to-indoor air pathway via indoor air sampling, researchers have suggested moving the focus of VI investigations outside the home. Several published studies have sampled soil, soil gas and ground water from the subsurface near and beneath potentially impacted homes. These measurements are often used with “generic” attenuation factors to estimate indoor air concentrations and subsequent risk to occupants. However, subsurface sampling is subject to spatial and temporal variability. For example, it is not known if moisture content measurements taken outside the building footprint are representative of moisture content directly beneath the building. This uncertainty may have a great impact on vapor intrusion predictions as vapors travel in air-filled pore space. Studies have also shown that soil gas concentrations may vary at different locations beneath buildings (Laubacher et al. 1997). Vapors may flow along more permeable routes associated with utility conduits, untrapped drains or naturally existing macropores. An important component of the potential

biodegradation of gasoline vapors is adequate oxygen supply in the subsurface. While one modeling study showed little impact of building foundation on oxygen concentrations in the shallow subsurface beneath a structure (Hers et al. 2000), another field study indicated anoxic locations directly beneath a slab (Laubacher et al. 1997). Temporal factors affecting subsurface measurements include seasonal changes in building depressurization due to the use of fireplaces, heaters, open windows, air conditioners or wind; the movement of subsurface soil gas from barometric pumping caused by both diurnal and longer-term atmospheric pressure changes; and temperature effects on contaminant partitioning. Moisture content will also change over time with climatic conditions controlling precipitation and evapo/transpiration. Precipitation may cause the water table to rise and with it the contaminant source zone. However, there is evidence that some gasoline components may become trapped beneath the infiltrating recharge, greatly reducing their ability to volatilize into soil gas - a phenomenon known as “plume diving” (Weaver and Wilson, 2000). The influence of water table fluctuation on NAPLs can result in repeated trapping and exposing of NAPL to soil gas. Drought conditions may lower the water table and expose previously-trapped NAPL product, greatly increasing the NAPL partitioning into soil gas. These and other conditions may confound synoptic field data and need to be addressed in order to provide practitioners with guidance as to under what conditions sampling should occur in order to provide a conservative, “worst-case” sampling event.

Finally, some researches have suggested using models with site-specific data in order to evaluate the vapor intrusion pathway. Site-specific data suffers from the

uncertainty described above. Models have their own additional challenges, often being either simplified and not accounting for all fate and transport processes or complex and containing unmeasured (or unmeasurable) parameters. The purpose of model usage is very important in determining the required level of detail in field data or assessment. A common use of vapor intrusion models is to screen out sites, or individual homes at sites, that are deemed to require no further investigation. For screening-level purposes, a simplified model may be appropriate if it can be shown to produce a “worst-case” prediction of current and future exposure in all cases. An example of the screening-level model is the widely used Johnson and Ettinger vapor intrusion model. One-dimensional diffusion through the unsaturated zone and advection and diffusion through the building slab are incorporated into the model, but biodegradation of organic vapors is not included. While this may be considered “conservative” with respect to occupant exposure to vapors, ignoring biodegradation of organic vapors may greatly over-estimate the potential exposure to aerobically degradable petroleum hydrocarbons. On the other end of the complexity spectrum are models that are used for detailed predictive analyses of current and future vapor exposures that are dependent upon site-specific parameters. These models might include multi-dimensional, multi-species vapor transport through the unsaturated zone with sorption to the soil moisture phase. Biodegradation could occur stoichiometrically (with oxygen concentration) in the soil-moisture phase with the rate being temperature dependent. While the additional level of complexity may help account for other fate and transport properties of the organic vapor, detailed multidimensional data for defining parameters and calibrating such a model are not routinely collected and suffer from the same spatial and temporal variability described previously. While several

vapor intrusion models have been published in the scientific literature, there has been little evaluation of the false-negative (type II) error produced by the models at field sites, with the possible exception of the widely-studied Johnson and Ettinger model (Fitzpatrick and Fitzgerald 2002, Johnson et al. 2002, Hers et al. 2003).

### **3 Vapor Intrusion Fate and Transport Mechanisms**

#### **3.1 Sources**

Contaminants of concern in vapor transport in the unsaturated zone are typically volatile organic compounds (VOCs), although vapors emanating from inorganic sources such as mercury vapor may be of concern as well. A chemical is considered to be volatile if its Henry's Law Constant is  $1 \times 10^{-5}$  atm-m<sup>3</sup>/mol or greater (Environmental Quality Management 2003). Examples of VOCs that are important in impacted environmental systems include chlorinated solvents such as carbon tetrachloride, tetrachloroethylene, and trichloroethylene (TCE), and their degradation compounds), fuel hydrocarbons such as benzene, toluene, ethylbenzene and *o,m,p*-xylenes as well as volatile pesticides such as chlordane, aldrin and lindane. The U.S. Environmental Protection Agency lists 107 compounds whose toxicity and volatility produce a potentially unacceptable inhalation risk to receptors (Environmental Quality Management 2003). These VOCs can be released into the subsurface environment from leaking landfill liners, improper disposal, accidental spillage, or leaking underground storage tanks (LUSTs). Once in the subsurface, these compounds can become bound to the soil matrix, dissolved in groundwater (or soil water) and/or exist as a separate, residual phase known as a non-aqueous phase liquid (NAPL). Soil, aqueous, and NAPL-phase organics

may all be sources of organic vapors in the subsurface. Therefore, organic vapor transport in the unsaturated zone requires understanding of interphase mass-transfer processes as the contaminant can be distributed between soil gas, water, soil, and NAPL phases.

### **3.2 Transport**

Organic vapors emanating from contaminated soil or groundwater or from a residual phase such as gasoline floating on the water table may move through unsaturated zone soil gas by diffusion or soil-gas advection due to pressure or density gradients or a combination of these processes.

#### **3.2.1 Diffusion**

Molecular diffusion is the spreading out of compounds from random collisions resulting from thermal motion of atoms. These collisions may be between molecules themselves or between molecules and their surroundings. Under most environmental conditions, molecular diffusion in natural systems proceeds from locations of higher concentration towards locations of lower concentrations. In a typical scenario, organic vapors above a contaminated water table (high concentration) diffuse towards land surface (lower concentration). The well-known relation describing the diffusion of a compound across a unit of cross-sectional area is *Fick's First Law*:

$$F_x = -D^{eff} \frac{dC}{dx}$$

where  $F_x$  is the mass flux [ $\text{ML}^{-2}\text{T}^{-1}$ ],  $D^{eff}$  is the effective diffusion coefficient of the compound in the gas phase [ $\text{L}^2\text{T}^{-1}$ ], and  $dC/dx$  is the concentration gradient of the compound in one-dimension [ $\text{ML}^{-3}\text{L}^{-1}$ ]. From this equation, it is apparent that the rate of molecular diffusion in the gas phase depends upon the concentration gradient and the effective diffusion coefficient of the compound of interest. Several relations exist that relate the effective diffusion coefficient to the free-air diffusion coefficient of the compound and the total and air-filled porosities of the diffusing media (Buckingham 1904, Penman 1940, Van Bavel 1952, Rust et al. 1957, Dye and Dallavale 1958, Millington 1959, Currie 1970, Nilson et al. 1991, Bartelt-Hunt and Smith 2002, Rolston and Moldrup 2002). An increase in diffusive flux is seen in soils with greater air passageways (i.e. greater porosities and air-filled porosities). Therefore, in a layered unsaturated zone, vapor diffusion from depth to land surface will be limited by the wettest, least porous soil layer. As free-air diffusion coefficients are compound dependent, ranging from  $2.5 \times 10^{-3} \text{ cm}^2\text{s}^{-1}$  for hexachloroethane to  $2.71 \times 10^{-1} \text{ cm}^2\text{s}^{-1}$  for chloroethane for the 107 volatile compounds of concern of USEPA (Environmental Quality Management 2003), different chemicals will diffuse at different rates under the same concentration gradients. Also, increased temperature produces an increased free-air diffusion coefficient, leading to a greater rate of diffusion relative to the same system at lower temperatures. Situations where Fick's First Law may not sufficiently describe vapor diffusion include systems where pore sizes are very small (Knudsen diffusion) and when volatile species constitute a substantial fraction of the total soil gas concentration (non-equimolar diffusion) (Thorstenson and Pollock 1989, Baehr and Bruell 1990,

Partridge et al. 2002). In these situations, it may be necessary to employ the more rigorous Stefan-Maxwell equation.

### **3.2.2 Advection**

The flow of soil gas (advection) in the subsurface may be caused by gas-pressure gradients or, in certain cases, gas density gradients. Pressure-driven advection is produced when differences in soil-gas pressure form, causing soil gas to flow and carrying any vapors present with it. Air pressure gradients in the subsurface of natural systems may result from several phenomena. As diurnal or weather related atmospheric pressure cycles occur at land surface, pressure waves are transmitted into the unsaturated zone and air may flow in response – a process known as “barometric pumping”. Barometric pumping may cause soil gas to flow either towards land surface carrying soil vapor or away from land surface bringing in fresh atmospheric air (Sleep and Sykes 1989, Thorstenson and Pollock 1989, Nilson et al. 1991, Massmann and Farrier 1992, Auer et al. 1996, Elberling et al. 1998, Tillman et al. 2001, Choi et al. 2002, Neeper 2002, Rossabi and Falta 2002, Tillman and Smith 2005). The underpressurization of an overlying building will produce gas pressure differences in subsurface soils. This underpressurization may be caused by thermal differences between indoor and outdoor air (stack effects), wind loading on the building superstructure, and imbalanced building ventilation (Nazaroff et al. 1987, Garbesi and Sextro 1989). Soil gas pressure gradients may also be produced by a rapidly rising or falling water table, as in coastal zones (Li et al. 2002), or through the buildup of gas pressure from decomposing organic matter inside a landfill (Little et al. 1992). Finally, natural temperature differences between warmer deep and cooler shallow soil gas will cause soil gas to rise (Gustin et al. 1997), (Krylov

and Ferguson 1998). Density-driven flow of organic vapors may occur in the vicinity of residual-phase organic compounds whose saturation gas densities are greater than that of air. As organic liquids with high vapor pressures and molecular weights volatilize, the density of the soil gas surrounding the liquid changes. In almost all cases, organic liquids have molecular weights which are greater than air so the resulting density-driven flow will be in a downward direction and be proportional to soil permeability and density differences between the vapor and air (Falta et al. 1989, Mendoza and Frind 1990a, Mendoza and Frind 1990b). Organic compounds for which density-driven advection may be significant include methylene chloride, 1,2-dichloroethylene, 1,1,1-trichloroethane, carbon tetrachloride and 1,1-dichloroethane, among others (Falta et al. 1989, Mendoza and Frind 1990a, Mendoza and Frind 1990b).

### **3.2.3 Sorption**

As organic vapors move through the unsaturated zone by diffusion and advection, they come in contact with soil moisture, infiltrating rainwater and the soil matrix itself. Each of these interactions may affect the concentration of the contaminant in the soil gas. Depending on the compound, organic vapors may adsorb to soil grain surfaces or partition into soil organic matter (Goss 1994b, a, Goss and Eisenreich 1996, Popovicova and Brusseau 1998, Ruiz et al. 1998, Goss et al. 2004). Adsorption of relatively non-polar organic vapors is suppressed by the presence of high humidity in the subsurface, as polar water molecules can effectively out-compete organic vapors for mineral-surface adsorption sites (Chiou and Shoup 1985, Smith et al. 1990). For these high-humidity conditions, sorption may be limited to organic vapor partition into soil organic matter

(Chiou and Shoup 1985, Smith et al. 1990). Soil moisture trapped in unsaturated-zone pore space or infiltrating rain water may also sorb organic vapors to varying degrees (Cho and Jaffe 1990, Cho et al. 1993). Finally, gas-phase organic compounds may adsorb to the air-water interface in unsaturated zones (Kim et al. 1997, Kim et al. 1998). Each of these sorption processes may act as both a source and a sink of organic vapors in the unsaturated zone.

### **3.2.4 Biodegradation**

Under favorable conditions, organic vapors in the unsaturated zone that partition into soil moisture may be biodegraded in oxidation/reduction reactions by indigenous bacteria. The aerobic biodegradation of petroleum hydrocarbons requires an abundant oxygen supply as well as necessary nutrients of nitrogen and phosphorus (Ostendorf and Kampbell 1991, Norris et al. 1994, Lahvis and Baehr 1996, Lahvis et al. 1999, Hers et al. 2000). When oxygen is depleted, other possible electron acceptors for biodegradation of petroleum hydrocarbons include nitrate ( $\text{NO}_3^-$ ), iron oxides (e.g.  $\text{Fe}(\text{OH})_3$ ), sulfate ( $\text{SO}_4^{2-}$ ) and carbon dioxide ( $\text{CO}_2$ ) (Norris et al. 1994). Lightly chlorinated compounds (e.g. chlorobenzene, dichlorobenzene) may be biodegraded under aerobic conditions. The more highly chlorinated hydrocarbons are recalcitrant to aerobic biodegradation but may undergo direct or cometabolic anaerobic reductive dechlorination.

Reductive dechlorination has been observed to be most effective under sulfate-reducing and methanogenic conditions (U.S. Environmental Protection Agency 2000). In direct reductive dechlorination, the chlorinated hydrocarbon is used as an electron

acceptor and the bacteria gain energy and grow as a result of the reaction (McCarty 1997). In cometabolic reductive dechlorination, enzymes produced during microbial metabolism of another hydrocarbon fortuitously reduce and dehalogenate the chlorinated contaminant. For either reductive dechlorination process to be successful, a primary substrate (electron donor) such as soil organic matter, lactate, acetate, methanol, or glucose is necessary (Vogel et al. 1987).

### **3.3 Building Effects**

The effects of overlying buildings play a very important role in the subsurface-to-indoor-air pathway. Different building construction techniques may have different impacts on the ability of vapors to enter indoor air space. Buildings with basements may have more surface area through which vapors can move inside, as well as be closer to subsurface sources than slab-on-grade buildings. A single-pour cement foundation may not have the “perimeter-crack” often associated with foundations whose footers and floor are poured separately, but may still become cracked along stress lines. Foundations and subsurface walls constructed from cement blocks may contain cracks around mortar that can allow subsurface gas to enter the building. Homes build over a crawl space may benefit from the dilution of soil gas by ventilated crawlspace air, but do not have the impedance to vapors that concrete slabs provide. A properly installed and sealed vapor barrier will provide resistance to vapor intrusion into crawlspaces. Building underpressurization relative to soil gas pressure can be caused by temperature differences between indoor and outdoor air (i.e. stack effects), imbalanced air handling systems,

wind, or barometric pressure cycles. Typical values for building underpressurization range from 2 to 10 Pa, but may be as high as 15 Pa during the heating season (Hers et al. 2001). The underpressurization of buildings relative to subsurface pressure may cause contaminated soil gas to flow into indoor air spaces, increasing exposure over diffusive transport alone. However, scientists are still working to define the zone of influence surrounding the building within which soil gas vapors are likely to flow into a building, and the effect of construction type and soil moisture on the breadth and depth of this zone. This soil gas flow can occur through untrapped drains, sumps, perimeter cracks, expansion/settling cracks or utility conduits. Conversely, a positive building pressure may greatly reduce the intrusion of subsurface vapors by causing air to flow out these same cracks and penetrations of the building envelope.

Once volatile contaminants enter a building, several processes come into play that have an effect on potential human exposure. Building ventilation may serve to reduce the indoor air concentration of vapors that emanate from the subsurface. Natural ventilation may occur through open windows, openings between windows or doors and walls, or through cracks in walls, foundations and floors. Mechanical ventilation may be provided by attic fans or, in the case of large buildings such as office buildings, with heating or cooling systems that utilize outside air (Olson and Corsi 2002). Ventilation is usually described in terms of air exchanges (or changes) per hour (ACH) and values for residential air exchange rates are usually on the order of ~ 0.1 to 1.0 ACH (Hers et al. 2001). If ventilation is occurring with uncontaminated outdoor air then indoor air concentrations will become diluted. Conversely, if outdoor air is contaminated, then

ventilation may become an additional source of vapors entering the home. In an indoor air study by (Brown 2002), it was estimated that 70% of the indoor VOC concentration resulted from unknown sources in the established dwellings that were sampled. Additionally, VOC pollution was one to two orders of magnitude higher in new and renovated buildings than in established dwellings, owing to building materials and furnishings. Dominant indoor sources of VOCs include latex paints, carpets, and tobacco smoke for benzene, with additional sources of wood burning, paint removers, adhesives/tape and solvents for toluene (Hers et al. 2001). The adsorption of VOCs by indoor materials will reduce peak concentrations, with desorption serving to prolong the presence of an indoor air contaminant (Meininghaus and Uhde 2002). In a laboratory study of sorptive interactions between VOCs and indoor materials by (Won et al. 2001), the authors identified carpet as the most significant sorptive sink for non-polar VOCs of the materials investigated (carpet, gypsum board, upholstery, vinyl and wood flooring, acoustic tiles, and fruit). Virgin gypsum board was observed to be a significant sink for highly polar VOCs. There are also significant seasonal variations in indoor air concentrations of VOCs, as discussed by (Rehwagen et al. 2003), who found the VOC load in indoor air approximately three times higher in the winter months than in summer in a 7-year study of indoor air in Germany.

## **4 Current Federal Regulations**

US Environmental Protection Agency (USEPA) has promulgated a “Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)” in the Federal Register dated November 29, 2002 (Volume 67, Number 230 - see <http://www.epa.gov/fedrgstr/EPA->

[AIR/2002/November/Day-29/a30261.htm](#) for a description). The guidance in this document is recommended for use at RCRA Corrective Action sites, CERCLA (National Priorities List and Superfund Alternative) sites, and Brownfields sites, but not recommended for use at Subtitle I Underground Storage Tank (UST) sites (U.S. Environmental Protection Agency 2002). As such, the contaminants for which this draft guidance will be used are mainly chlorinated solvents and will not routinely involve petroleum hydrocarbons (a common fuel in underground storage tanks). This guidance document does not impose any requirements or obligations on EPA, states, or the regulated community, and the sources of authority and requirements for addressing subsurface vapor intrusion currently remain the relevant statutes and regulations (e.g., RCRA, CERCLA and the NCP).

Procedures in the draft guidance for evaluating vapor intrusion include a tiered screening system. Primary screening (Tier 1) involves obtaining knowledge of the chemicals present at the site, determining if they are sufficiently volatile and toxic to pose a potential threat, and determining if inhabited buildings are located (or will be constructed) above or in close proximity to the subsurface contamination. If primary screening does not rule out the vapor-to-indoor air pathway, then Secondary screening (Tier 2) is recommended. Secondary screening involves comparing measured or “reasonably estimated” concentrations of contaminants in either ground water, soil gas or indoor air, to generic attenuation factors for a particular risk level. If unacceptable exposure cannot be ruled out from the generic attenuation factor, measured concentrations are compared to attenuation factors based on soil type and depth to

contamination. These screening level concentrations were derived using the (Johnson and Ettinger 1991) simplified model. If Tier 2 screening cannot rule out vapor intrusion, then a Site-Specific Pathway Assessment (Tier 3) is recommended. This tier requires direct measurement of foundation air and/or indoor air concentrations from a subset of potentially effected buildings, and complementary site-specific modeling as appropriate. USEPA's Office of Emergency and Remedial Response (OERR) publishes a "User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings" (Environmental Quality Management 2003) to be used as a companion for the draft guidance document. This user's guide includes detailed information on using OERR-distributed spreadsheets that run the Johnson and Ettinger model (U.S. Environmental Protection Agency 1999) which are available at [http://www.epa.gov/superfund/programs/risk/airmodel/johnson\\_ettinger.htm](http://www.epa.gov/superfund/programs/risk/airmodel/johnson_ettinger.htm). If a significant risk for vapor intrusion cannot be ruled out then remedial action may be required, as determined by the site manager.

#### **4.1 States**

Under the Leaking Underground Storage Tanks Program (LUST), individual states are required to address accidental petroleum discharges within their borders. As there is no federally-mandated requirement to evaluate the vapor intrusion pathway, states' responses to vapor intrusion from petroleum leaks vary greatly and are evolving as science and policy in this field progress. Several state regulations include the evaluation of vapor intrusion as a potential exposure pathway of organic contaminants. Links to many of these states' documents can be found at <http://www.envirogroup.com/links.htm> or [http://www.geosyntec.com/vi\\_links.asp](http://www.geosyntec.com/vi_links.asp). Additionally, the Interstate Technology &

Regulatory Council (ITRC) publishes a background document for vapor intrusion at Brownfield sites (<http://www.itrcweb.org/BRNFLD-1.pdf>) and is currently at work on a document discussing vapor intrusion issues at petroleum-contaminated sites.

## 5 Vapor Intrusion in the Field

Few peer-reviewed articles exist in the scientific literature that present indoor air and subsurface vapor data from sites impacted by vapor intrusion of VOCs. However, several newspaper articles receiving national attention were published in the Denver Post in early 2002 by journalist Mark Obmascik about human exposure to 1,1-Dichloroethene (DCE) vapors from the contamination at Denver's Redfield rifle scope factory (Obmascik 2002e, a, c, d, b). This series of articles were highly critical of EPA's use of the simplified Johnson & Ettinger model to screen sites for potential vapor intrusion.

In evaluating the Johnson and Ettinger model, Hers et al. (2003) present a review of previously published data from several field sites with contamination from both chlorinated and BTEX compounds. Sources ranged from 0.5 m to 10.7 m below foundation and included both ground water and soil gas sources. For petroleum hydrocarbon sites, measured vapor attenuation factors ranged from  $\sim 10^{-7}$  to  $10^{-5}$ . For chlorinated solvent sites, ground water attenuation factors were on the order of  $10^{-5}$  to  $10^{-4}$  for the most reliable data sets. The authors conclude that, for almost all cases, the best estimate Johnson and Ettinger model-predicted attenuation factors were one to two orders of magnitude more conservative than 50<sup>th</sup> percentile or median measured values.

One of the most thoroughly studied vapor-intrusion sites in the United States is the Colorado Department of Transportation Materials Testing Laboratory (CDOT-MTL) located in Denver, CO. More than 1,000 groundwater, soil gas, and indoor air samples were analyzed (cost estimated >\$1,000,000) in studying the potential impacts of chlorinated solvent contamination in soil and groundwater (Johnson et al. 2002). The authors of this study note that assessing the significance of the subsurface-to-indoor air pathway via direct measurement is likely to be impracticable at many sites and recommend using limited site data (depth to groundwater, qualitative soil boring data, and approximate building characteristics) with a screening level model such as Johnson & Ettinger. Empirically-derived vapor attenuation factors for the site fall in the range of  $10^{-6}$  to  $10^{-4}$ , with an overall average of  $3 \times 10^{-5}$ .

In Fitzpatrick and Fitzgerald (2002), the authors present a review of Massachusetts VOC-contaminated field site data in order to determine field attenuation coefficients and evaluate the J&E transport model in predicting indoor air concentrations. To identify sites where ground water VOC contamination impacted indoor air, a database search was conducted on over 6,000 files maintained by the Massachusetts Department of Environmental Protection (MADEP) in its Northeast Regional Office, servicing 95 cities and towns in the greater Boston metro area representing a population of 3 million people (roughly half the state's population). An initial search for impacted indoor air resulted in a list of 165 sites, which were investigated to determine if annual average depth to ground water is  $\leq 5\text{m}$  below ground surface and ground water contamination exists within 10m of an occupied building. Of the 165 sites, 68 had relevant ground water, soil gas and/or

indoor air data. The list was narrowed to include sites with high-quality data and to eliminate sources in soil and 47 sites and sub-sites were selected from these criteria. Of the 47 sites identified, 26 (55%) had been impacted by chlorinated VOCs, while 21 (45%) were associated with gasoline releases. No site had been impacted by both classes of compounds. Of the impacted buildings, 24 (52%) were residential homes, 1 (2%) was a school, and 21 (46%) were commercial buildings. Attenuation coefficients were calculated for 22 sites with available indoor air and soil gas data with values ranging from  $2 \times 10^{-6}$  to  $1 \times 10^{-1}$ . Attenuation at TCE sites (11) ranged from  $9 \times 10^{-5}$  to  $9.7 \times 10^{-2}$  while benzene sites (3) ranged from  $1.5 \times 10^{-5}$  to  $4 \times 10^{-5}$ . Groundwater concentrations of VOCs protective of indoor-air exposure, codified by MADEP as “GW-2 Standards”, were calculated by the agency using the Johnson and Ettinger model. Out of the 35 relevant study sites with available GW and IAQ data, three had VOC levels in ground water below acceptable GW-2 standards and also had acceptable VOC measurements in indoor air. Unacceptable indoor air concentrations were measured at 15 sites which exceeded the GW-2 standards. Of these 15 sites, 14 were associated with chlorinated VOCs and 1 was associated with a gasoline release. 13 sites with ground water concentrations above GW-2 standards exhibited acceptable levels of indoor air VOCs. Of these sites, 10 were related to gasoline releases with the other 3 above a TCE plume. Lastly, 4 sites had unacceptable indoor air concentrations but GW concentrations less than GW-2 standards. Based on a review of the data, authors conclude that attenuation for chlorinated VOCs appear to be about 2 orders of magnitude higher than the  $5 \times 10^{-4}$  value used in developing the MADEP GW-2 standards and attenuation values for chlorinated VOCs appear to be significantly higher than values for nonchlorinated VOCs.

It appears that the GW-2 standards for chlorinated sites may not be protective of indoor air exposures, while standards derived for nonchlorinated sites are adequate. It is difficult to draw conclusions regarding the extent of vapor intrusion of petroleum hydrocarbons from this study due to only three sites with benzene contamination having data quality sufficient to calculate an attenuation coefficient. However, a state-wide review of field-collected data such as this that is subject to data-quality and peer-review has potential to be very useful in establishing actual expected ranges of exposure to subsurface vapors in a wide range of sites and climatic conditions.

Fischer et al. (1996) present a report of a field-study of soil-gas transport of VOCs into a building at a former gasoline station at the Alameda Naval Air Station (ANAS) in California. High VOC concentrations ( $30\text{-}60\text{ g m}^{-3}$ ) were measured in soil gas 0.7-m below the building. Indoor air concentrations had attenuated by  $\sim 10^6$  due to a sharp gradient in soil-gas concentrations between 0.1 and 0.7 m (attenuation of  $\sim 10^3$ ) and the dilution of soil gas entering the building by wind-driven building ventilation (an attenuation factor of  $\sim 10^3$ ).

Moseley and Meyer (1992) published an air, soil-gas and groundwater monitoring study investigating the source and extent of petroleum contamination in an elementary school located adjacent to a gasoline station and a petroleum tank farm in the Midwest. Ground water and soil-gas data indicated a contaminant plume had formed between a tank known to have leaked 20,000 gallons of gasoline and the school building. After odor complaints by staff and students at the school, the local fire department measured

levels of airborne vapors up to 40% of the lower explosive limit, and the school was evacuated. Subsequent investigations involving air samples taken inside the school revealed benzene concentrations that were slightly elevated over outdoor concentrations. However, indoor total hydrocarbon concentration (THC) levels were up to 40 times outdoor levels. Authors noted many possible indoor sources of THC including paint, ink, clothing, gas and oil heating systems, and cleaning agents. Concentrations found in the school below floor level were significantly higher than both indoor and outdoor measurements. Crawlspace vapors were 2600 parts per billion (ppb) benzene, compared with no-detect (ND)-5 ppb in the classroom. Crawlspace THC concentrations were 120,000 ppb, compared with 530-2600 ppb in classrooms.

Hodgson et al. (1992) present a study at a single-family residence located approximately 70m from a landfill perimeter in Stanislaus County, CA. The house was a single-story structure build over a basement and a garage. Twenty six VOCs were identified in soil gas samples, mainly halogenated hydrocarbons and oxidized compounds. Thirteen compounds were also detected in indoor air, although at very low concentrations (6 ppb or less). Authors conclude that the existence of soil-gas contamination alone is not sufficient to result in significantly elevated indoor exposures.

A line-leak at a petroleum distribution terminal that had been operating for about 70 years produced a dissolved-phase gasoline plume in the groundwater that migrated beneath a residential neighborhood, described in a study by Laubacher et al. (1997). No NAPL-phase contamination was noted and dissolved HC concentrations in two

monitoring wells have varied from 12,000 to 39,000 ppb total BTEX. TPH, CO<sub>2</sub> and O<sub>2</sub> data from outside the building slab indicate that aerobic bioactivity may be occurring down to a depth of approximately 10 feet below ground surface, and anaerobic activity from 10 ft to the water table. Vapor profiles from beneath the building indicate that the vadose zone beneath the basement is completely anaerobic. Authors state that this suggests that the hydrocarbon-vapor plume has accumulated beneath the basement slab because it is less permeable to diffusion. Indoor air was sampled on “a number of occasions” and never produced readings greater than control homes (1-2.2 ppb benzene). This study is significant in that it presents data indicating an anaerobic zone may occur beneath a building due to oxygen replenishment limitations. Even though this anaerobic region would eliminate aerobic biodegradation of petroleum vapors, there is no evidence in this study of increased vapor concentration inside the home.

Hers and Zapf-Gilje (1998) and Hers et al. (2000) present data from the Chatterton field site located near Delta, BC (near Vancouver). This former petrochemical plant has BTX residual NAPL distributed over a 1-m interval at the water table. Regular soil gas monitoring was used to assess the effect of seasonal changes on soil gas fate and transport with vadose zone. A small greenhouse was built on a 6.1 × 9.3-m at-grade concrete slab to investigate vapor intrusion into buildings. Indoor air, outdoor air, and flux chamber measurements were conducted in and around the greenhouse under both static and dynamic (mechanical ventilation) conditions. Results indicate that BTX concentrations were similar at vapor probes located near the north, east and south edges of the slab. In contrast, BTX concentrations directly below the west edge of the slab

were slightly higher, and BTX concentrations at the probe directly below the slab were significantly higher (> 2 orders of magnitude). Statistical hypothesis testing indicated that, in all but one case, the mean indoor and outdoor concentrations were significantly different for the dynamic case (using a two-tailed test and significance level of 0.10). Differences were not statistically significant for the static case.

Although not a peer-reviewed scientific journal, a recent publication by the petroleum industry group “American Petroleum Institute” by Roggemans et al. (2001) presents an empirical assessment of soil gas profile data from previously published, unpublished and two new petroleum hydrocarbon release sites. The objective of the study was to assess whether or not the soil gas data was consistent with the occurrence of aerobic biodegradation. While evidence of biodegradation of organic vapors was seen for several of the sites, the authors were unable to correlate the lack of signs of biodegradation with the presence of surface features such as pavement, buildings or with very wet surface soils. Of the 28 soil-gas profiles presented, 7 (25%) were able to be fit by a model considering diffusion-only and no biodegradation. Additionally, the authors compared flux predicted using the deepest available soil gas concentration with flux computed using the concentration measured closest to land surface. While 6 of the data sets presented indicate vapor fluxes attenuated by two to four orders-of-magnitude, in 5 of the 15 sets (33%) the effect of aerobic biodegradation was seen to be insignificant.

## **6 Review of Vapor Intrusion Models**

The following is a brief review of several vapor intrusion models that have appeared in the scientific literature or in conference proceedings. The intent here is not to present an exhaustive description of each model, but to introduce the approach and features that make each of them unique. While much of the current understanding of vapor intrusion of organics into buildings stems from research on radon intrusion into buildings, only models dealing specifically with organic vapors are presented here. Readers are directed to Clements and Wilkening (1974), Schery et al. (1984), Schery et al. (1988b, a), Nazaroff (1992), and Holford et al. (1993) for further information on radon modeling.

Paul Johnson and Robert Ettinger (1991) present the first major modeling effort of vapor intrusion of VOCs into indoor air. Beginning with the general, transient transport equation that includes advection, diffusion, and formation in 4 phases (vapor, sorbed, free phase and soil moisture), the authors develop a “heuristic” (i.e., for the purposes of education or problem solving) equation for predicting indoor air concentration from soil data. The free-phase is assumed to be small enough to ignore, and the sorbed phase is not included in further model development, leaving only the aqueous and vapor phases. The vapor phase is related to the aqueous phase through Henry’s law and diffusive transport is assumed significant only in the vapor and soil moisture phases. The Millington (1959) approximation is used for estimating the effective diffusion coefficient through the unsaturated zone from porosity and moisture content information. Vapor flow in response to building depressurization is described by Darcy’s law. Next, chemical and biological transformations are ignored and a steady-state solution is assumed. Diffusive

transport from the source to a region near the structure is approximated by discretized Fick's law, incorporating an overall effective diffusion coefficient for subsurface layers. The diffusion length is taken to be the distance between the source and the foundation – assuming that convection, when significant, is only dominant in a region very near the foundation. Uniform convective velocity is approximated by dividing soil gas velocity by crack area. The mass transport rate by diffusion between source and foundation is set equal to the mass entry rate of contaminant into the building and solved for soil gas contaminant concentration. This result is substituted into the steady-state, 1-d solution to the transport equation to obtain the rate of contaminant entry into the building. The relationship for the rate of contaminant entry is incorporated into a steady-state mass balance for a basement or building to produce an explicit expression for indoor air concentration. This indoor air mass balance assumes no other sources or sinks and a well-mixed building. An attenuation coefficient ( $C_{\text{building}}/C_{\text{source}}$ ) is produced containing three dimensionless groups: one the equivalent Peclet number, one the attenuation coefficient for diffusion-dominated transport to a bare-dirt floor, and one the attenuation coefficient for convective transport from a source located adjacent to the building (i.e. no diffusion length). Three limiting situations are examined: convection as the dominant mechanism through floor and walls, diffusion the dominant mechanism, and no building ventilation. The solution is extended to accommodate diffusion through permeable below-grade walls rather than foundation cracks. Finally, expressions are presented for evaluating if a transient solution is appropriate and a transient solution for depleting sources is derived. A sensitivity analysis is presented for several parameters including crack-factor and air permeability. A separate review of the Johnson and Ettinger model

with a detailed sensitivity analysis is also presented in (Johnson 2002) and (Johnson 2005).

Little et al. (1992) present a first-order estimate of the elevation in indoor VOCs from subsurface contamination analogous to radon transport. Authors state that VOC attenuation coefficients would be smaller because radon emanates from soil right next to the building and VOCs must be transported over some distance. Model assumptions include a constant source, isotropic and homogenous medium, and that VOCs are immediately swept into the building when they arrive at the zone of influence. A one-dimensional, diffusion-only model utilizing the Millington and Quirk relation for effective diffusion coefficient and retardation (assuming linear sorption to soil moisture) is presented. The resulting indoor air concentration is estimated as the rate of VOC mass entering the building divided by the volumetric flow rate of air through the building. A transient solution for an attenuation coefficient is presented for a planar source at depth  $L$  diffusing through originally uncontaminated soil. A second transient attenuation coefficient solution is presented for a uniform source of contamination surrounding the building. Finally, a one-dimension advection/sorption model is presented incorporating a Darcy velocity for vapor transport from a landfill to a building. A steady-state solution is given along with estimated time for the contaminant to travel from the landfill to the building.

Sanders and Stern (1994) adapt two previously published time-varying, deterministic models to predict indoor air concentrations and dose. The Little et al.

(1992) vapor-intrusion model was modified to allow first-order decay of the contaminant source. The Jury et al. (1990) vapor transport model was multiplied by the area of influence of the depressurized building and divided by the building air flow rate to obtain indoor air concentration. Expressions for dose (integration of the product of concentration and inhalation rate) for both models are also presented.

Ferguson et al. (1995) present an equilibrium, analytical, 3-box model for indoor air concentration. Linear partitioning is assumed between soil, soil gas and soil water. Fickian molecular diffusion is allowed between the following three compartments: soil, living space, and outdoor space (including attic). Diffusion between each compartment is presented as a series of diffusion through layers comprising the boundaries of the compartment (e.g. through concrete, insulation, decking, etc.). Suction flow is allowed and determined using Darcy's law, with pressure difference measured between indoors and soil-gas pressure (taken as equal to atmospheric pressure) and pressure flow length (characteristic path length) assumed to be 1 meter. This length is the path length of the flux beneath outside walls. Ventilation is computed from air exchanges per hour. A time averaged production term [ $\mu\text{g/hr}$ ] is introduced to allow for indoor sources of contamination (e.g. cigarettes, paints, oils glues, cleaning fluids, etc.). All of these terms are combined in a mass balance equation to determine indoor air concentration. Five limiting cases are derived from the general mass balance: no indoor contamination sources; unpolluted soil and polluted outdoor air; unpolluted outdoor air; unpolluted soil; unpolluted outdoor air and unpolluted soil (i.e. indoor sources only). Finally, a first-order

decay process of benzene in bulk soil, due to volatilization and chemical/biological degradation, is incorporated.

Waitz et al. (1996) present a spreadsheet-based risk assessment model incorporating human exposure to VOCs in indoor air that is unique in its applicability to homes on crawl spaces. Sources for the model include well-mixed groundwater contamination both beneath the structure and intercepting the crawl space, a floating soil-contaminant layer both beneath the structure and intercepting the crawl space, a trapped NAPL phase in the unsaturated zone, and a NAPL phase beneath the water table. Contaminant fluxes are calculated assuming linear, equilibrium partitioning between soil-water and soil-gas (Henry's Law) and linear partitioning between soil and soil-water (linear sorption isotherm). Both diffusion and pressure-driven flow are allowed in the unsaturated zone. Air flux from the crawl space through the floor into indoor air is driven by advection. An indoor air concentration is computed from this flux and ventilation and air-exchange rates

Jeng et al. (1996) begin their model development with a one-dimensional unsteady-state mass balance partial differential equation containing vapor, water and solid phases and first-order degradation. Simplifying assumptions include no advective flux, both vapor and liquid phase diffusion are described by Fick's law (with Millington-Quirk effective diffusion coefficient), degradation occurs only in the liquid phase and the rate constant is based only on the dissolved concentration. Linear equilibrium relationships are assumed between water/air phases (Henry's Law) and soil/water phases

( $K_D$ ). Boundary conditions of an exponentially depleting source and no change in concentration at infinite distance are used along with an initial condition of zero concentration to develop an analytical solution to the transport equation (taken from van Genuchten and Alves (1982)). Vapor flux is calculated from concentration data. Concentration in a building is obtained from the product of area, volume, air exchanges and flux. Several cases are presented for comparison including a constant source with no retardation or attenuation; a constant source with retardation but no degradation; a constant source with water and soil partitioning and including degradation; and a depleting source with all attenuation mechanisms. A sensitivity analysis is performed on water content, organic carbon content and degradation/source depletion.

Sanders and Talimcioglu (1997) compare the previously published modifications to the Jury et al. (1990) model (Sanders and Stern 1994) with a second model named the Integrated Moisture Plus Contaminant Transport (IMPACT) model. IMPACT is a 2-dimensional model designed for the calculation of soil cleanup criteria for hazardous waste sites as controlled by the soil-to-groundwater pathway, but also includes the volatilization pathway. The model incorporates equilibrium partitioning, diffusive, degradation, and mass-balance processes equivalent to the Jury model, but also includes hydrodynamic dispersion. It can also simulate soil moisture contents and moisture transport (using Richard's equation and Darcy's Law). An expression for hydraulic conductivity is used, and soil moisture retention and soil diffusivities are calculated by the Clapp and Hornberger (1978) empirical equation. The contaminant transport and moisture flow equations for IMPACT are solved using numerical techniques. The

modified Jury model and the IMPACT model are compared under hypothetical and actual moisture content data.

Krylov and Ferguson (1998) present a model incorporating diffusive and advective transport between different model compartments (similar to Ferguson et al. (1995)). Diffusive transport is allowed from soil to crawl space, from crawlspace to outdoor air, from crawlspace to living space, and from living space through walls and ceiling. Advective transport may occur from soil gas to crawlspace (by wind-induced pressure gradients, from crawlspace to living space (from stack and ventilation effects), from crawlspace to outdoor air (by ventilation of crawlspace), from living space to outdoor air (by ventilation of living space). These diffusive and advective fluxes are used in flux balance equations to derive indoor air concentration. Effective diffusion coefficients between compartments are computed from individual layers by Millington relation and inverse summed for total layer diffusivity. Soil gas flow is assumed to a depth of 1 m. A relation for pressure gradients based on wind speed is incorporated. Resulting solution is a steady-state, analytical relationship between indoor air concentration and compartmental diffusions, air flow rates, surface areas, initial soil concentration and partition coefficient (including air, soil and water partitioning). A first-order decay process for total soil concentration is added to account for volatilization and biodegradation effects on source concentration. Permissible bulk soil concentrations for benzene indoor air concentration of 5 ppb are determined for differing wind loadings and building systems.

Ririe et al. (1998) modify a mathematical approach given in an unpublished presentation by J. Gustafson in 1997 that was originally used for laboratory studies of diffusion and biodegradation. This equation relates a normalized concentration profile ( $c/c_o$ ) to exponential terms that include a first-order degradation constant and an effective diffusion coefficient. An expression for attenuation is also given, defined here as the ratio of surface flux with and without biodegradation. Authors also describe the Orange County Health Care Agency (OCHCA) Vapor Transport Model that includes source partitioning from water (Henry's Law) or liquid phase (Raoult's Law) and transport by diffusion. Attenuation through a slab is determined by a "slab factor". Flux is instantaneously mixed in the building and is in dynamic steady-state with the exchange rate (ventilation) of building air with outside air. Flux may also occur from the subsurface to outside air, and then enter the building by air exchange. Authors propose plotting field data with Gustafson relationship to curve-fit a bioattenuation factor. This factor can then be used in the OCHCA model to determine flux.

Johnson et al. (1998, 1999) present refinements to the Johnson and Ettinger (1991) J&E model. A vapor source expression is presented that assumes a single-component, linear-partitioning relationship and three phase equilibrium (vapor, sorbed, dissolved phases) source. A relation is given for estimating time to steady state, derived from solution to transient diffusion with step-change boundary condition at time zero. An additional relation is presented for a concentration profile with first-order biodegradation. This first-order relation is then incorporated into the J&E attenuation equation. A family of type-curves is presented to facilitate determining biodegradation

rate constant from field data. Equations for describing a “dominant-layer” of degradation are presented and incorporated into attenuation expression.

Olson and Corsi (2001) present an exposure model based on mass balance equations for two compartments: basement and ground floor. Processes include air flow from ambient (outdoor) to basement, air flow from basement to ground floor and ground floor to basement, and a term for the pollution emission rate from soil to the basement. Simplifications allow for CSTR-type equations to be integrated, producing a time-varying solution for pollutant concentrations in the basement and first floor. Steady-state solutions are also provided. Mass intrusion was evaluated from a measured SF<sub>6</sub> emission rate, Darcy’s Law and a steady-state mass balance.

Parker (2003) developed a model to assess human exposure and health risk associated with VOC emissions to indoor air. This model considers a finite source mass; vapor transport due to advection, diffusion, and barometric pumping; oxygen-limited biodecay; and building underflow. A relationship for vapor source above a dissolved contaminant in groundwater (that incorporates changes in aqueous concentration with time) involving Henry’s Law is presented. An average source concentration over a defined time period is also presented. Vapors above a NAPL source are computed using Raoult’s law, with relationships for the decrease in NAPL thickness due to volatilization (leaching is ignored) and time to deplete the COC from the entire NAPL source also presented. For transport, a solution to quasi-steady-state diffusion is presented with the effective diffusion coefficient including both Millington tortuosity and dispersion from

barometric pumping. Relations for mean Darcy velocity at ground surface as well as the depth-averaged velocity are given. The depth of barometric pressure propagation is taken as the lesser of the depth to ground water (capillary fringe), or max depth limited by permeability (a relationship is provided to determine this depth). Biodecay rate per soil volume is the lesser of (1) the maximum, non-oxygen-limiting “intrinsic” rate, (2) the rate limited by diffusion oxygen transport from the soil surface or soil-building interface, or (3) the rate limited by oxygen from air flowing from soil under the building (by wind). Relationships are given for each of these cases. A relationship is also given for the increased volatilization that will result from biodegradation of vapors. For mixtures of hydrocarbons, the total potential for decay is distributed among multiple species; a relative biodecay rate (of dissolved-phase concentrations) is computed and included in each of the rates mentioned above. The Parker model uses the Johnson and Ettinger (1991) model for advective and diffusive transport into a building while adding terms accounting for loss due to airflow under the building and biodecay.

## **7 Conclusions and Future Work**

The intrusion of organic vapors from the subsurface into indoor air spaces may be a human health concern from either carcinogenic or toxic exposures. While much attention has been focused on vapor intrusion in recent years, many challenging issues remain. It is still unclear, based on published studies, whether or not the problem is widespread in nature or just confined to a few sites where climatic, hydrogeologic and other conditions serve to link the subsurface-to-indoor air pathway. Difficulty in evaluating whether or not VI is occurring stems from the temporal and spatial variability

in soil gas and sub-slab measurements, unknown indoor sources confounding indoor air sampling, and a lack of information on the accuracy of models. While the Johnson and Ettinger (1991) model is widely used and has become the de-facto model of choice for screening sites for vapor intrusion, the model is still not routinely used with a thorough uncertainty analysis to obtain a range of reasonable outputs.

Continued research in the field of vapor intrusion will focus on providing answers and guidance towards overcoming these current limitations. A national database of data from vapor intrusion sites currently being identified will help to identify the extensiveness of the problem. Improvements in field data collection including identifying and removing indoor VOC sources before performing indoor air sampling could greatly aid in establishing the vapor intrusion pathway. Additional research in measuring flux at land surface outside the footprint of a building may provide researchers with information on seasonal variability in VOC flux in the subsurface. Investigations into the critical parameters of subsurface vapor transport, particularly moisture movement beneath buildings, should be performed. Finally, users who rely on models for vapor intrusion screening and risk assessment should be provided with models that automatically incorporate uncertainty of input parameters and provide a range of outputs. This would allow users to gain confidence in model predictions or allow users to better focus their efforts in obtaining field data to improve model uncertainty.

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