GENERAL CONCEPTS OF MASS-FLUX-BASED SCREENING FACT SHEET

Introduction

The purpose of this fact sheet is to describe how mass-flux-based screening methods can be used as part of the vapor intrusion (VI) screening process. As noted in **Section 5.4.2**, VI is governed by the rate at which vapor-forming chemical (VFC) mass migrates from the subsurface, across a building foundation, and into and out of an enclosed indoor air space per unit time. If the VFC migration is assumed to be one-dimensional or vertically upward, then that rate can be defined in terms of mass flux or the rate of VFC mass flow through the building foundation (per unit area) and per unit time. Mass discharge is an analogous term that describes the volumetric airflow of VFCs from the subsurface to indoor air (Q_{soil}) and within and out of a building ($Q_{building}$). Mass discharge represents the mass flux integrated over the entire area of the building foundation and is expressed in terms of volume per unit time. The ratio of $Q_{soil}/Q_{building}$ represents the foundation (or slab) attenuation factor (AF) for the building assuming a conservation of mass and no background (non-VI) sources of VFCs in indoor air (McAlary, Gallinatti, et al. 2018) (see the **Attenuation Factors Fact Sheet**).

Mass flux can do the following:

- Provide a measure of the potential impact to indoor air.
- Reduce the uncertainties associated with
    - VFC concentrations in indoor air and sub-slab soil vapor that can vary by several orders of magnitude within a given building over time and space (Folkes et al. 2009; Holton et al. 2013; Luo et al. 2009); and
    - Background and non-VI-related sources of VFCs in indoor air (see **Section 2.2.4 Background Sources of Chemicals** and the **Background Sources to Indoor Air Fact Sheet**).
- Be used to estimate the maximum concentrations for current and future conditions.
- Be determined from limited site sampling.
- Support mitigation design and performance evaluations (see **Section 7.7.2: Differential Pressure Monitoring and Building Pressure Control**, and the **Pressure Monitoring and Building Pressure Control Fact Sheet**).
- Yield estimates of building-specific AFs and sub-slab soil-vapor screening levels.

The challenge with mass-flux-based screening is that estimating the VFC mass flux using methods other than the application of simple VI models or spreadsheet tools (see **Chapter 9: VI Modeling**) can be challenging to obtain, requiring relatively sophisticated tools, equipment, and experienced personnel. In addition, direct application of mass flux for the purpose of "site screening" has not been reported in the literature even though mass-flux tools are increasingly being applied in VI assessments. Practitioners are thus encouraged to consult with the applicable regulatory authority for approval.

For VI assessments, mass flux (or discharge) is either

a. Simulated using VI models based on conservation of mass principles, such as Johnson and Ettinger (1991), BioVapor (API 2010), PVIScreen (USEPA 2016), and PVI-2D (Yao et al. 2017) or vapor transport models that are described in Hers et al. (2002) and Yao et al. (2013); or

b. Quantified directly from airflow and VFC concentration measurements in off-gas emissions associated with sub-slab or indoor air depressurization.

VFC mass-flux estimates obtained from VI modeling can be determined from groundwater or soil-gas concentration measurements at specific locations or from a vertical (depth-discrete) profile of soil-gas concentration measurements (Lahvis et al. 1999) (see **Chapter 5: Site Screening, Figure 5-3a**). These concentration measurements are typically made at or between a VFC source and a current or future building. The models are used to predict concentrations in indoor air from mass-flux (or discharge) estimates using default or site-specific vadose zone and building properties as model input, where:

$$C_{IA} = \frac{mass\ discharge}{AER * Vol_{Building}} \qquad \textbf{(Equation 1)}$$

where C_{IA} is the concentration of VFC in indoor air (mass/volume); *mass discharge* is the rate of VFC entry into the building or occupied structure (mass/time); *AER* is the building air exchange rate (1/time); and $Vol_{Building}$ is the building or occupied structure volume (length^3). Model estimates of C_{IA} are highly sensitive to both *AER* and $Vol_{building}$. These variables can, however, be easily estimated or approximated. $Vol_{Building}$ estimates can be based on default parameter values, for example 244 m^3 for a one-story, single-family residence (USEPA 2004), or building-specific estimates or measurements of aerial building footprint and building height/basement depth. *AER* values are published in ASHRAE (1985), Koontz and Rector (1995), and USEPA (2011). For residential buildings, the mean *AER* value reported in USEPA (2011) is 0.45/hour, and the tenth percentile *AER* is 0.18/hour. *AER* values for nonresidential buildings are more variable depending on heating, ventilation, and air conditioning (HVAC) and facility operations. USEPA (2011) reports a mean AER value of 1.5/hour for commercial/industrial buildings.

Model estimates of VFC transport in the vadose zone are sensitive to the effective diffusion coefficient (D_{eff}) of the vadose zone soil and rates of aerobic VFC biodegradation. The D_{eff} are either assumed based on generic (default) soil properties reported in the literature (USEPA 2004), site-specific soil properties from geotechnical analyses (e.g., moisture content, total porosity) of field samples and application of the Millington and Quirk (1961) relation, or estimated via in situ using tracer testing (Johnson et al. 1998; Tick et al. 2007). It is important to note that model predictions of indoor air concentrations from measurements of VFC concentrations in groundwater will be highly uncertain. The uncertainty stems from an inability to quantify VFC concentrations at the water table; highly variable D_{eff} that vary by several orders of magnitude across the capillary zone; and, at VI sites with more biodegradable VFCs, rates of aerobic biodegradation. Aerobic biodegradation rates of VFCs are reported in Howard et al. (1991), DeVaull et al. (1997), and the **BioVapor Model Fact Sheet**. Rates of aerobic VFC biodegradation will largely be governed by the availability of O_2 in the vadose zone, and in turn, the land-surface boundary condition (e.g., constant O_2 concentration or constant O_2 air flow) represented by a building foundation (e.g., crawl space/earthen floor, concrete slab-on-grade). Additional information on estimating mass flux using transport models can be found in **Chapter 9: Modeling**.

Rates of VFC mass flux or discharge into buildings can also be directly quantified by depressurizing the air inside or below a building or occupied space foundation (see **Chapter 5: Site Screening, Figures 5-3b and 5-3c**, respectively). Indoor air depressurization is commonly termed building pressure control (BPC) and involves a combination of negative and positive pressurizations using a blower door to induce or inhibit VI (Lutes et al. 2019; McAlary 2019; McAlary, Wertz, et al. 2018; McHugh et al. 2012; NFESCA 2021). Mass-flux (or discharge) rates are calculated from measurements of VFC concentrations and airflow rates across the blower door (Q_{BPC}). The mass-flux (or discharge) rates are then used to estimate maximum exposure concentrations for VFCs in indoor air by applying **Equation 1**, which can then be compared to risk-based screening levels in indoor air. In addition, BPC can be used to assess AER and the influence of preferential pathways and background (non-VI) sources on VI. BPC can be challenging to apply in certain commercial/industrial buildings, however, especially ones with multiple rooms and zones of HVAC operation. To help address this issue, the U.S. Navy developed best practices for BPC implementation in large commercial/industrial buildings. The best practice includes information on how to adjust HVAC operation as an alternative to blower doors (NFESCA 2021). Key design elements of BPC are also reported in Lutes et al. (2019). Sub-slab depressurization is achieved by applying sub-slab depressurization (McAlary 2019; McAlary, Wertz, et al. 2018) (see **Chapter 10: Vapor Intrusion Mitigation**) or high-volume sampling (McAlary, Wertz, et al. 2018; McAlary et al. 2020; Nicholson et al. 2021). Mass-flux (discharge) rates are calculated from measurements of VFC concentrations and airflow (Q_{SSG}) in vent pipes. The mass-flux (discharge) rates are again used to estimate concentrations of VFCs in indoor air, which then can be compared to risk-based screening levels (see **Chapter 5: Site Screening**, **Section 5.4.1 Concentration-Based Screening**) by applying **Equation 1**. The implementation of sub-slab depressurization methods for mass-flux determinations is reported in the Environmental Security Technology Certification Program (McAlary 2019; McAlary, Wertz, et al. 2018), which includes case studies of sub-slab depressurization technologies that were used to obtain site-specific estimates of AFs and sub-slab soil vapor screening levels.

REFERENCES

API. 2010. "BioVapor Indoor Vapor Intrusion Model." **https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/vapor-intrusion/biovapor**.

ASHRAE. 1985. *ASHRAE Handbook, 1985 Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

DeVaull, G. E., R. A. Ettinger, J. P. Salanitro, and J. B. Gustafson. 1997. *Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX) Degradation in Vadose Zone Soils during Vapor Transport: First-Order Rate Constants*. CONF-971116-. December 31, CONF-971116-. **https://www.osti.gov/biblio/569942**.

Folkes, D. J., W. Wertz, J. Kurtz, and T. Kuehster. 2009. "Observed Spatial and Temporal Distributions of CVOCs at Colorado and New York Vapor Intrusion Sites." *Groundwater Monitoring & Remediation* 29 (1): 70–80. **https://doi.org/10.1111/j.1745-6592.2009.01216.x**.

Hers, Ian, Reidar Zapf-Gilje, Dyfed Evans, and Loretta Li. 2002. "Comparison, Validation, and Use of Models for Predicting Indoor Air Quality from Soil and Groundwater Contamination." *Soil and Sediment Contamination: An International Journal* 11 (4): 491–527. **https://doi.org/10.1080/20025891107140**.

Holton, Chase, Hong Luo, Paul Dahlen, Kyle Gorder, Erik Dettenmaier, and Paul C. Johnson. 2013. "Temporal Variability of Indoor Air Concentrations under Natural Conditions in a House Overlying a Dilute Chlorinated Solvent Groundwater Plume." *Environmental Science & Technology* 47 (23): 13347–54. **https://doi.org/10.1021/es4024767**.

Howard, Philip H., Robert S. Boethling, William F. Jarvis, William M. Meylan, and Edward M. Michalenko. 1991. *Handbook of Environmental Degradation Rates*. 1st ed. CRC Press. **https://www.routledge.com/Handbook-of-Environmental-Degradation-Rates/Howard/p/book/9780367402990**.

Johnson, P. C., C. Cruce, R. Johnson, and M. Kemblowski. 1998. "In Situ Measurement of Effective Vapor-Phase Porous Media Diffusion Coefficients." *Environmental Science & Technology* 32 (21): 3405–9.

Johnson, P. C., and R. A. Ettinger. 1991. "Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings." *Environmental Science & Technology* 25 (8): 1445–52. https://doi.org/10.1021/es00020a013.

Koontz, M. D., and H. E. Rector. 1995. "Estimation of Distributions for Residential Air Exchange Rates." USEPA Office of Pollution Prevention and Toxics. https://nepis.epa.gov/Exe/ZyNET.exe/910063GS.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000025%5C910063GS.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.

Lahvis, Matthew A., Arthur L. Baehr, and Ronald J. Baker. 1999. "Quantification of Aerobic Biodegradation and Volatilization Rates of Gasoline Hydrocarbons near the Water Table under Natural Attenuation Conditions." *Water Resources Research* 35 (3): 753–65. https://doi.org/10.1029/1998WR900087.

Luo, H., P. Dahlen, P. C. Johnson, T. Peargin, and T. Creamer. 2009. "Spatial Variability of Soil-Gas Concentrations near and beneath a Building Overlying Shallow Petroleum Hydrocarbon−Impacted Soils." *Groundwater Monitoring & Remediation* 29 (1): 81–91. https://doi.org/10.1111/j.1745-6592.2008.01217.x.

Lutes, Christopher C., Chase W. Holton, Robert Truesdale, John H. Zimmerman, and Brian Schumacher. 2019. "Key Design Elements of Building Pressure Cycling for Evaluating Vapor Intrusion—A Literature Review." *Groundwater Monitoring & Remediation* 39 (1): 66–72. https://doi.org/10.1111/gwmr.12310.

McAlary, T. A. 2019. *Demonstration/Validation of More Cost Effective Methods for Mitigating Radon and VOC Subsurface Vapor Intrusion to Indoor Air: Mitigation System Optimization*. U.S. Department of Defense: ESTCP. https://apps.dtic.mil/sti/trecms/pdf/AD1134960.pdf.

McAlary, T. A., J. Gallinatti, G. Thrupp, W. Wertz, D. Mali, and H. Dawson. 2018. "Fluid Flow Model for Predicting the Intrusion Rate of Subsurface Contaminant Vapors into Buildings." *Environmental Science & Technology* 52 (15): 8438–45. https://doi.org/10.1021/acs.est.8b01106.

McAlary, T. A., W. Wertz, and D. Mali. 2018. *Demonstration/Validation of More Cost-Effective Methods for Mitigating Radon and VOC Subsurface Vapor Intrusion to Indoor Air*. U.S. Department of Defense: ESTCP. https://clu-in.org/download/issues/vi/ER-201322-Final-Report.pdf.

McAlary, T. A., W. Wertz, D. Mali, and P. Nicholson. 2020. "Mathematical Analysis and Flux-Based Radius of Influence for Radon/VOC Vapor Intrusion Mitigation Systems." *Science of the Total Environment* 740 (139988).

McHugh, Thomas E., Lila Beckley, Danielle Bailey, et al. 2012. "Evaluation of Vapor Intrusion Using Controlled Building Pressure." *Environmental Science & Technology* 46 (9): 4792–99. https://doi.org/10.1021/es204483g.

Millington, R. J., and J. P. Quirk. 1961. "Permeability of Porous Solids." *Transactions of the Faraday Society* 57 (0): 1200–1207. https://doi.org/10.1039/TF9615701200.

NFESCA. 2021. *Optimization of Building Pressure Cycling Methods for Vapor Intrusion Studies in Large Buildings*. Naval Facilities Engineering Systems Command Atlantic. https://exwc.navfac.navy.mil/Portals/88/Documents/EXWC/Restoration/er_pdfs/b/BPC%20Optimization%20TM_05_03_21.pdf?ver=DqOWIWCMiAxEcKpzRsnC9g%3D%3D.

Nicholson, Paul, Darius Mali, and Todd A. McAlary. 2021. "Simplified Approach for Calculating Building-Specific Attenuation Factors and Vapor Intrusion Mitigation System Flux-Based Radius of Influence." *Groundwater Monitoring & Remediation* 41 (2): 122–31. https://doi.org/10.1111/gwmr.12456.

Tick, Geoffrey R., Colleen M. McColl, Irfan Yolcubal, and Mark L. Brusseau. 2007. "Gas-Phase Diffusive Tracer Test for the In-Situ Measurement of Tortuosity in the Vadose Zone." *Water, Air, and Soil Pollution* 184 (1): 355–62. https://doi.org/10.1007/s11270-007-9403-3.

USEPA. 2004. *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings*. United States Environmental Protection Agency Office of Emergency and Remedial Response. https://www.epa.gov/sites/default/files/2015-11/documents/2004_0222_3phase_users_guide.pdf.

USEPA. 2011. *Exposure Factors Handbook 2011 Edition (Final Report)*. U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

USEPA. 2016. *Petroleum Vapor Intrusion Modeling Assessment with PVIScreen*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100TJ1S.PDF?Dockey=P100TJ1S.PDF.

Yao, Yijun, Rui Shen, Kelly G. Pennell, and Eric M. Suuberg. 2013. "Examination of the Influence of Environmental Factors on Contaminant Vapor Concentration Attenuation Factors Using the U.S. EPA's Vapor Intrusion Database." *Environmental Science & Technology* 47 (2): 906–13. https://doi.org/10.1021/es303441x.

Yao, Yijun, Iason Verginelli, and Eric M. Suuberg. 2017. "A Two-Dimensional Analytical Model of Vapor Intrusion Involving Vertical Heterogeneity." *Water Resources Research* 53 (5): 4499–513. https://doi.org/10.1002/2016WR020317.