NJDEP Technical Guidance Document Review Form

Document: ***Vapor Intrusion Technical Guidance Version 5.0 (draft)***
ATTORNEY CLIENT WORK PRODUCT – PRIVILEGED AND CONFIDENTIAL

Comment Period START: October 15, 2020
Comment Period END: October 30, 2020 (Revised to November 16, 2020)

Send all comments to NJDEP Committee Chairperson Carey Compton at: Carey.Compton@dep.nj.gov

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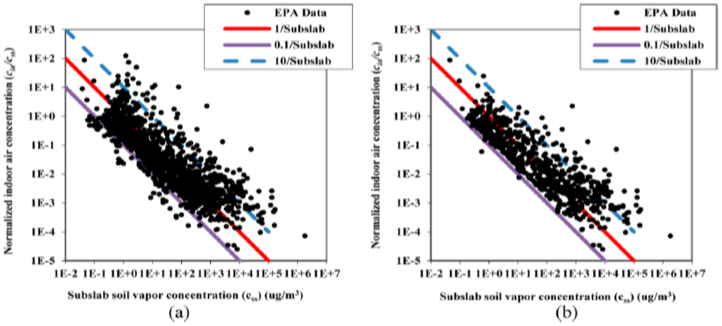
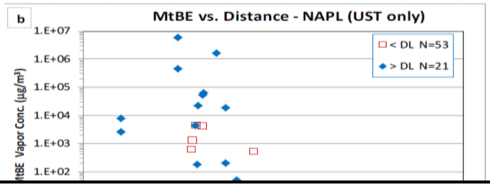
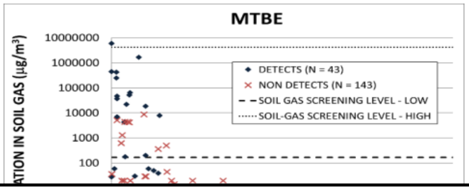
Comment #	**Page**	**Section**	**Subsection**	**COMMENTS**
				General
1	General			The Vapor Intrusion Technical Guidance version 5.0 (VITG) is being issued to address the proposed Draft Remediation Standards (Docket 01-20-03), which proposes the establishment of Indoor Air Remediation Standards (IARS) for the first time. The implementation of remediation standards will increase the complexity and technical scrutiny associated with all VI projects. CCNJ/SRIN appreciate the opportunity to review the VITG, however we are disappointed the NJDEP has limited our review and comment of this very important document to the "revised portion of the document only." As presented in our comments there are several details that should be addressed within the VITG that would benefit the public, the NJDEP staff and the regulated community.
2	General			The VITG includes only minor modifications compared to the current version 4.1, January 2018. The current VITG has been used for the past 34 months, thus the regulated community has developed questions, concerns and discrepancies that should be addressed in this new document. The following observations and questions, which have been identified by LSRPs and the regulated community, identify a portion of the comments that would improve the effectiveness of the revised VITG **and are relevant to the indoor air remediation standards.** 4.2.1.3 - The VITG should explain how the ambient air data validity assessment should be conducted. Is this the same as all other data validity assessments or is the NJDEP proposing something special? 4.2.1.3 - The VITG should explain how an elevated ambient air concentration may be presented to the NJDEP and how additional VI investigations should proceed. The VITG simply states "mitigation will not be required when the site specific ambient air results are in excess of the IA results." Will additional investigations be required? Will additional sampling be required? Will "step-out" investigations of the ambient air and indoor air quality be required? 4.2.1.4 - The VITG should explain how the median chemical concentration from the NJDEP background air study will be used as a line-of-evidence in evaluating the IA analytical results when the VITG specifically forbids the subtraction of the background air concentration for site specific samples.

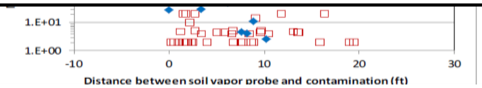
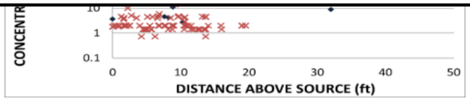
3	General	The VITG includes only minor modifications compared to the current version 4.1, January 2018. The current VITG has been used for the past 34 months, thus the regulated community has developed questions, concerns and discrepancies that should be addressed in this new document. The following observations and questions, which have been identified by LSRPs and the regulated community, identify a portion of the comments that would improve the effectiveness of the revised VITG **and are relevant to the indoor air remediation standards.** 4.2.1.4 - The NJDEP IA study focused on indoor air sampling to determine background levels of VOCs in homes. By definition, any detection of a VOC within the indoor air samples represents background air conditions. The NJDEP should justify why the median concentrations should only represent IA background conditions in New Jersey. What is the rationale for ignoring the upper 50% of the data set? The USEPA has established guidelines on the determination and evaluation of background contaminants which generally utilize an upper tolerance limit for the background concentrations and not the median value, which is arbitrarily determined by the number of samples that are included. 6.4.2.3 - The VITG should provide guidance on how to evaluate a malfunctioning passive VI mitigation system given that most passive systems involve a membrane/liner system only.
4	General	The NJDEP fails to identify the specific legal authority under which the adoption of new indoor air remediation standards is authorized. The document references four statutes (i.e. N.J.S.A.13:1D-1 et seq., 58:10-23.11a et seq., 58:10A-1 et seq., and 58:10B-1 et seq.) as the alleged source of the Department's authority, but none of these statutes grant the Department the specific authority to establish indoor air remediation standards. For example, N.J.S.A. 58:10B-1, et seq. is the Brownfield and Contaminated Site Remediation Act (the "Brownfields Act"). The Brownfields Act grants express statutory authority to the NJDEP to "adopt minimum remediation standards for soil, groundwater, and surface water quality necessary for the remediation of contamination of real property." (N.J.S.A. 58:10B-12(a)). This statutory provision further requires the Department to "develop minimum remediation standards for soil, groundwater, and surface water intended to be protective of public health and safety taking into account the provisions of this section." It is unclear why the Department feels compelled to unduly expand its authority to promulgate indoor air remediation standards, particularly when the Proposed Amendments lack justification or quantification of a reduction of risk to public health or the environment.
5	General	The VITG is being issued to address the proposed Draft Remediation Standards (Docket 01-20-03), which proposes the establishment of IARS for the first time. Within the proposed rules, the NJDEP committed to "amending existing technical guidance and developing new technical guidance documents to assist the regulated community in applying the remediation at contaminated sites." (Overview statement) The VITG fails to provide guidance to the regulated community regarding the detection of very low chemical concentrations within indoor air samples with subsequent remediation standard exceedances creating vapor concern (VC) conditions. The following points identify specific details that should be included within the revised document to assist the Public, the NJDEP staff and the regulated community to effectively manage environmental projects while protecting human health and the environment.

6	General			The proposed IARS for ten (10) compounds will be equal to their individual detection limits including very commonly used chemicals (Benzene, Carbon tetrachloride, 1,2-Dibromoethane (Ethylene dibromide), 1,2-Dichloropropane, 1,3-Dichloropropene (total), 1,4-Dioxane, Mercury (elemental), Naphthalene, 1,2,4-Trichlorobenzene, Trichloroethene (TCE)). For these 10 compounds, the indoor air analysis will focus on a Presence or Absence chemical evaluation while any detection will impose a VC condition (N.J.A.C. 7:26E-1.15(e)6) on the site. The NJDEP should recognize that the detection of any chemicals within the IA space of a home is very stressful for all parties including the residents, the property owners, the responsible parties, the LSRP and the NJDEP staff. The NJDEP should provide specific guidance detailing the Lines of Evidence techniques and alternatives that will be quickly accepted by the Department to define the fraction of the detected chemicals associated with background conditions and the remaining fraction of chemicals that may be caused by VI. The Draft VITG only states "ambient air results" cannot be subtracted from the analytical results; however additional guidance is necessary when a VC condition is encountered, especially for the common chemicals with IARS equal to their detection limits. In addition, the NJDEP should recognize that Petroleum Vapor chemical differentiation (fingerprinting) is much more difficult than Chlorinated VOC Vapor differentiation. Given the ubiquitous nature of refined petroleum compounds, multiple unsubstantiated VC cases will be needlessly generated without the intervention of reasonable scientific theories.
7	General			The VITG includes only minor modifications compared to the current version 4.1, January 2018. A review of the evaluation of the reference list suggests the document does not include recent research regarding VI. Only two of the 46 references have been published in the last 5 years and 65% of the references were published more than 10 years ago. Researchers continue to document the complex interaction of IA with the surrounding environment and subgrade conditions. As an example, researchers for *Strategic Environmental Research and Development Program* (SERDP) have documented indoor air can negatively affect shallow soil conditions beneath a crawl space for weeks after the IA source is removed (SERDP, Project ER-1686, July 2016). The SERDP research is just one example of recent research which expands the understanding of VI complexities. An expanded review of recent research will improve the effectiveness of the VITG for the regulated community and also more effectively support the NJDEP reviewers.
				Specific
1	24	3	1.3	The VITG changes the NJDOH reporting policy, but the section should address the short timeframes as mandated by the Tech Regs for "step-out" investigations, especially considering the common chemicals which will trigger a VC condition simply by their detection in IA. The proposed IARS for ten (10) compounds will be equal to their individual detection limits including very commonly used chemicals (Benzene, Carbon tetrachloride, 1,2-Dibromoethane (Ethylene dibromide), 1,2-Dichloropropane, 1,3-Dichloropropene (total), 1,4-Dioxane, Mercury (elemental), Naphthalene, 1,2,4-Trichlorobenzene, Trichloroethene (TCE)). Any detection of these compounds within an IA sample will trigger a VC condition, which mandates an expanded investigation of all adjacent buildings within 150 days, referred to as a "step-out" investigation. The "step-out" investigation must continue in 150-day increments for the expanded investigation buildings including receipt of laboratory indoor air data, identification of step out structures, evaluation of the structures, finalization of access agreements, investigation of indoor air conditions, performance of indoor air sampling, and receipt of indoor air analytical data. If there is any detection of these 10 compounds, the 150-day "step-out" requirement continues. The VITG should provide a provision to allow the LSRP to provide justification to temporarily stop the 150-day "step-out" requirement while the LSRP evaluates the first indoor air concentrations. The VITG does not allow an ARS for a residential building, but an evaluation of background chemicals is reasonable and should be addressed within an amended VITG.

2	37	3	3.1.4 Table 3.2	Table 3-2, Recommended ***Minimum*** Number of Sub-Slab Soil Gas (SSSG) Samples, has changed greatly without explanation. The VITG states to "**utilize the table below as a minimum number of samples and add additional samples** based on the building-specific features and conditions provide below the table." Within the next paragraph the NJDEP states "Sub-slab sampling requirements cannot be based on area alone.", however Table 3-2 generally mandates one SSSG sample per every 1,670 square feet of building footprint. Table 3-2 and the text are a contradiction. Further, the VITG allows an LSRP to "evaluate the features and use of a building based on professional judgement to determine the number of sub-slab samples." Table 3-2 should not be revised as proposed.
3	37	3	3.1.4 Table 3.2	Table 3-2, Recommended Minimum Number of Sub-Slab Soil Gas (SSSG) Samples, has changed greatly without explanation. In the current VITG, a 250,00 square feet building will require 8 SSSG samples. Under the proposed VITG the same building would require 33 to 160 samples. This is a 20-fold increase in sample density, without explanation or justification for the change. This will greatly affect project complexity, site disruption and project costs without any large improvement of the knowledge of the site conditions. There is no text describing the reason or rationale for this change. Amending Table 3-2 without any explanation will also affect ongoing remedial investigations. The VITG is silent on how an LSRP should integrate this vastly greater sampling density into an active project with an active sample dataset. At a minimum, the NJDEP should identify the expected phase-in period for the enlarged sample density. Section 3-2 should remain unchanged as the minimum number of SSSG samples. If the NJDEP believes a greater sample density is justified, the VITG should explain the conditions that would justify the greater sample density and allow the LSRP to integrate these concerns into their investigation strategy.
4	37	3	3.1.4-Table 3.2	Please find two embedded articles that are relevant to the comment beginning, Table 3-2. Yao, Y., Shen, R., Pennell, KG, Suuberg, EM, *Examination of the U.S. EPA's Vapor Intrusion Database Based on Models* , Environmental Science and Technology, January 2013, p 1425 -1433. Lahvis, MA, Ettinger, RA, *Improving Risk-Based Screening at Vapor Intrusion Sites in California,* accepted for publication October 2020. Yao et al. (2013).pdf Document

5	37	3	3.1.4 - Table 3.2	Table 3-2, Recommended Minimum Number of Sub-Slab Soil Gas (SSSG) Samples, has increased greatly without technical justification. Recent science has shown that indoor air concentrations are poorly correlated with subsurface vapor concentrations (see plot below and references). Hence, increasing the number of sub-slab soil gas samples at commercial/industrial buildings based simply on the building footprint will not improve VI characterization/screening. In addition, most VI sites will have undergone some initial site characterization to develop a CSM that documents subsurface source (soil/GW) locations and potential pathways (openings/cracks) in the building foundation that should be targeted for subslab sampling. Blanket recommendations to increase the number of subslab locations based solely on the square footage of a building foundation size are thus not technically defensible. The NJDEP should refrain from increasing the number of subslab vapor points at commercial/industrial buildings with large building foundations because they will add little value for VI screening and risk assessment unless there is no information about the location/extent of the subsurface vapor source or locations of cracks/openings in the foundation that would be more susceptible to VI.  (a) (b) Figure 3. Measured subslab-to-indoor air concentration attenuation factor for (a) all contaminants (b) PCE and TCE in EPA's VI database.[2]
6	76	6	1.1.6	The proper citation for this discussion on proactive VI mitigation is 7:26E-1.15 since it is specific to the VI pathway. The sentence should read "The sampling requirements for structures having any proactive VI mitigation system should follow Receptor Evaluation procedures found in N.J.A.C 7:26E-1.15."
7	76	6	1.1.6	The purpose of the sub-slab soil gas sampling in situations with proactive mitigation is unclear from the discussion in Section 6.1.1.6. Is the intent of this VI sampling to determine if the VI pathway is complete, and thus whether mitigation is required at the building in question? Alternatively, is the VI sampling designed to determine whether the mitigation proactively installed during building construction is effective at cutting off the VI pathway and is considered more of verification sampling? The answer to the question of intent could determine whether commissioning, verification or OM&M is necessary. Thus, the location of the sub-slab soil gas sample collection relative to any vapor barrier could result in different conclusions. Clarification from the NJDEP is necessary.
8	95	6	5.1 - Table 6.1	Table 6-1: For SSDS, the only clear and reliable metric is vacuum under the slab; we suggest making IA sampling optional given the confounding issues from indoor air source.
9	95	6	5.1 - Table 6.1	Table 6-1: For passive system, please explain what an annual inspection of the system should include, and please explain how to check passive systems for malfunctioning, then modify or augment the system.

10	104	Appendix A	**Vapor intrusion triggers** - VI screening levels in soil gas (SGSL) and groundwater are based on an AF of 0.02. There is no technical justification provided for the AF. One can assume that the NJDEP's AF is based on a statistical analysis (i.e. 95th %) of empirical vapor concentration data and that it was supported by the AF = 0.03 determined by USEPA (2012). The derivation of an AF based on empirical vapor concentration data and a 95th % is **<u>fundamentally</u>** flawed because of a) a poor correlation between indoor air and subsurface vapor concentration data (see plots shown earlier from Yao et al. 2013) and (b) the inability to account for the spatiotemporal variabilities using discrete (in time and space) vapor concentration measurements. Indoor air and subsurface vapor concentrations are defined by air flow that is not accounted for or documented by the discrete concentration measurements. AFs must therefore be based on mass flux principles (such as those described in the Johnson and Ettinger 1991 model) or alternative methods, such as the reliability assessment described by the USEPA (2015) and Lahvis and Ettinger. Both the AF derived from the Johnson and Ettinger model using default parameters and the AF resulting from reliability analyses are likely to be closer to 0.001. The use of an overly conservative AF = 0.02 is therefore likely to trigger unnecessary VI assessments that divert limited resources from VI sites posing the greatest risk. The NJDEP is urged to review the latest science (e.g. Lahvis and Ettinger) and base SGSLs based on Johnson and Ettinger modeling rather than an AF = 0.02.
11	104	Appendix A	**Vapor intrusion triggers** - The VITG needs to capture the latest science on site screening, in particular for MTBE and the lead scavengers, 1,2 Dichloroethane (1.2 DCA) and 1,2-Dibromomethane (EDB). MTBE has been shown to attenuate in the vadose zone to a greater extent than benzene, on which the screening distances recommended by the NJDEP are based. The attenuation and vertical screening distances for MTBE can be inferred from Plot 1 (USEPA, 2013) and Plot 2 - data from the USEPA PVI database supplemented with additional data from Massachusetts. Hence, the screening distances recommended by the NJDEP are conservative for MTBE. It is also important to recognize that MTBE vapor attenuation is becoming more significant over time because of the removal of MTBE from gasoline (~15 years ago) and the weathering that has taken place since (i.e. screening distances for MTBE are only becoming shorter over time). The lead scavenger 1,2-DCA has also been shown by Kolhatkar et al. (2019) to attenuate below screening levels of concern for vapor intrusion over distances of 15 ft for both LNAPL and dissolved-phase sources The VITG should be revised to account for the application of vertical screening distances at sites with MTBE and 1,2-DCA. Not making this revision will only trigger unnecessary site characterization, increase reliance on IARS, and detract from being able to focus limited resources on locations where the VI pathway is most likely. Kolhatkar, R.V., Lahvis, M.A., Hers, I., Wilson, J.T., Luo, E.H., and P. Jourabchi. 2019. <u>Vertical screening distance criteria to evaluate vapor intrusion risk from 1,2-Dichloroethane (1,2-DCA)</u>. Groundwater Monit. Remediation, 38, 41-51.  

12	127	Appendix G		  Appendix G provides the derivation and application of the Vapor Intrusion Standards, Screening Levels, and Alternative Values to evaluate and remediate the VI pathway. The VITG states "An indoor air Alternative Remediation Standard (ARS) may be developed on a site-specific basis pursuant to N.J.A.C. 7:26D-8 with Departmental approval required prior to use at a site or AOC. An indoor air ARS cannot be established for a residence, school or childcare facility (N.J.A.C. 7:26D-Appendix 9)." Specifically, Brownfield Act N.J.S.A. 58:10B-12 (f)(1) states "A person performing a remediation of contaminated real property, in lieu of using the established minimum soil remediation standard for either residential use or nonresidential use adopted by the department pursuant to subsection c. of this section, may submit to the department a request to use an ***alternative residential use or nonresidential use soil remediation standard*** ." It is not clear that the Department is authorized to provide an option for a site-specific indoor air alternative remediation standard.
13	127	App. G	1	IARS Basis and Background documents are not available for review and comment. It is critical for stakeholders to understand how the NJDEP is utilizing the input parameters to calculate the IA standards in order to provide meaningful feedback. By understanding the input parameters, the LSRP and PRCR can develop ARS for their sites. Without the guidelines used by the NJDEP, such ARS are not likely to reach concurrence. We are requesting the release of these documents to be reviewed and commented on appropriately.
14	128	App. G	1.1	The VITG states: "Departmental approval is required prior to implementation of an indoor air ARS. The time required to develop and obtain approval of an indoor air ARS is not a justification for exceeding applicable regulatory and mandatory timeframes, as provided in the Administrative Requirements for the Remediation of Contaminated Sites (ARRCS), N.J.A.C. 7:26C-3, available at http://www.state.nj.us./dep/srp/regs/arrcs/index.html. As a result, the investigator should start the process for approval of an indoor air ARS as early as possible." In this section, the NJDEP recognizes potential time delays however it is not clear that the NJDEP considered the staffing and technical expertise that will be required to address the increased number of sites which may be inaccurately characterized as VC sites due to the very low detection limits. The VITG should include targeted timeframes for NJDEP review of VC conditions and all cases which include background contaminants. The regulated community recognizes complex sites require additional time, however the NJDEP solely controls the time required to receive NJDEP approval for many tasks.
15	128	App. G	1.1	The VITG states: "The investigator may propose an indoor air ARS for the VI pathway at a site or AOC at any time provided sufficient information is available to justify the basis of the indoor air ARS." What "sufficient information" will the Department deem acceptable? The Departments needs to clearly outline what specific information is needed to justify an indoor air ARS at a site or AOC.
16	128	App. G	1.1	Although the NJDEP's calculation tool is referenced, a search of the webpage site does not find the calculator. Stakeholders cannot effectively replicate or validate calculations or evaluate the VITG without being able to review the calculator function (and the basis and background for its development as provided by the USEPA for its RSL calculator). We are requesting the release of the calculators for the ARS to be reviewed and commented on appropriately.
17	129	App. G	1.1.1	The VITG states: "Pursuant to the ARRCS (N.J.A.C. 7:26C-7), the Department shall require the use of an institutional control, engineering control (as needed), and a remedial action permit to ensure that continued use of the indoor air ARS remains valid." Indoor Air Standards are not remediation standards (soil, ground water or surface water) and, therefore, institutional and engineering controls are not applicable in accordance to the Brownfields Act, N.J.S.A. 58:10B-13. Therefore, we request the removal of this requirement.

18	129	App. G	1.1.2	The inability to change default parameters used in calculating the default SRS for residential or non-residential land use, except for physical parameters for the inhalation exposure pathway, significantly limits the use of ARS. The ability to develop ARS on a site/AOC specific basis is a core component of many other state regulatory programs and the USEPA. ARS have been proven to be protective remedial measures and should be further promoted as the NJDEP attempts to address the impacts of climate change. For example, the development of ARS may reduce the need to install engineering controls (caps). Knowing that many of the properties requiring capping are located in urban centers ARS may assist in reducing the "heat island effect", which is an initiative of the USEPA (https://www.epa.gov/heatislands).
19	131	App. G	1.2	Within this section (Indoor Air Background Databases), the NJDEP notes that the median concentrations for indoor air sampling in New Jersey are representative of background conditions. With the establishment of IARS equal to the detection limit for 10 compounds, the VITG should expand on the discussion of the acceptable, the preferred and any unacceptable lines of evidence to evaluate the true effect of vapor intrusion verses background/ anthropogenic conditions. The Draft VITG should provide guidance describing how the Indoor Air Background databases identified in section 4.2.1.4 may be used as a LOE and any limitations on the use of these databases when evaluating a VC condition. The proposed VITG identifies the databases, but offers no techniques or methods utilizing the databases. Defining the acceptable and the preferred LOE will provide a more robust and relevant guidance document that can decrease the response time when a VC condition is identified.
20	131	App. G	1.2	The VITG states "Pursuant to the Brownfield and Contaminated Site Remediation Act, N.J.S.A. 58:10B-12, whenever a ***site is remediated to a non-residential standard*** , the Department shall require that use of the property be restricted to non-residential and that access to the site be restricted in a manner compatible with the allowable use of the property. Chapter 6 of this document includes information on the use of institutional and engineering controls for the VI pathway." Specifically, Brownfield Act N.J.S.A. 58:10B-12 (c)(1) states "The Department shall develop residential and nonresidential soil remediation standards that are protective of public health and safety...Whenever real property is ***remediated to a nonresidential soil remediation standard*** , except as otherwise provided in paragraph (3) of subsection g. of this section, the department shall require, pursuant to section 36 of P.L.1993, c.139 (C.58:10B-13), that the use of the property be restricted to nonresidential or other uses compatible with the extent of the contamination of the soil and that access to that site be restricted in a manner compatible with the allowable use of that property." Specifically, Brownfield Act N.J.S.A. 58:10B-12 (g)(2) states "Contamination may, upon the department's approval, be left onsite at levels or concentrations that ***exceed the minimum soil remediation standards for residential use if the implementation of institutional or engineering controls*** at that site will result in the protection of public health, safety, and the environment at the health risk standard established in subsections a., b., c. and d. of section 36 of P.L.1993, c.139 (C.58:10B-13), and paragraphs (1) and (10) of this subsection, are met. The department may also require the treatment or removal of contaminated material that would pose an acute health or safety hazard in the event of failure of an engineering control;" Therefore, we recommend the removal of the use of institutional and engineering controls for the VI pathway.
21	131	App. G	2	The VITG states "Consistent with the development of an indoor air ARS, Alternative Soil Gas Screening Level (SGSL) and Alternative Indoor Air Rapid Action Levels (RAL) are not applicable to residential properties. Alternative SGSL and Alternative Indoor Air RAL may be developed for non-residential properties based on site specific use of a non-residential building and approved indoor air ARS (see Section G.1.1)". Section G1.1 does not state that alternative SGSL and alternative indoor air RAL can be calculated for non-residential properties and what factors can be adjusted for these alternative standards. It is not clear if the "calculator" developed by the NJDEP provides the calculation for the alternative SGSL and alternative indoor air RAL.
22	135	App. G	2.2 & 2.2.1	The VITG states "The equations, input parameters and procedures used in the development of the SGSL are discussed in the VISL B&B document that can be assessed at http://www.nj.gov/dep/srp/guidance/vaporintrusion." This document is not available for review and comment. It is critical for stakeholders to understand how the NJDEP is utilizing the input parameters to calculate the SGSL and alternative SGSL in order to provide meaningful feedback. By understanding the input parameters, the LSRP and PRCR can develop ARS for their sites. Without the guidelines used by the NJDEP, such ARS are not likely to reach concurrence. We are requesting the release of these documents to be reviewed and commented on appropriately.

23	135	App. G	2.2.1	The VITG states "A calculator developed by the Department to assist the investigator in the generation of Alternative SGSL can be accessed at http://www.state.nj.us/dep/srp/guidance/rs/index.html." Although the NJDEP's calculation tool is referenced, a search of the webpage site does not find the calculator. Stakeholders cannot effectively replicate or validate calculations or evaluate the guidance document without being able to review the calculator function for Alternative SGSL. We are requesting the release of the calculators for the Alternative SGSL can be reviewed and commented on appropriately.
24	136	App. G	2.2.2	The VITG states "Soil gas results that do not exceed the SGSLs may or may not suggest further investigation." We are requesting NJDEP to clarify why soil gas results that are below SGSLs would warrant further investigation.
25	136	App. G	2.3 & 2.3.1	The VITG states "The procedures used in the derivation of the RAL are discussed in the VISL B&B document that can be accessed at https://www.nj.gov/dep/srp/guidance/vaporintrusion/." This document is not available for review and comment. It is critical for stakeholders to understand how the NJDEP is utilizing the input parameters to calculate the Indoor Air RAL and alternative RAL in order to provide meaningful feedback. By understanding the input parameters, the LSRP and PRCR can develop ARS for their sites. Without the guidelines used by the NJDEP, such ARS are not likely to reach concurrence. We are requesting the release of these documents to be reviewed and commented on appropriately.
26	136	App. G	2.3.2	The Draft VITG should provide guidance regarding the use and reporting of pneumatic testing procedures to evaluate the pneumatic pathway between subslab and indoor air conditions. Defining the acceptable and the preferred LOE will provide a more robust and relevant guidance document that can decrease the response time when a VC condition is identified.
27	136	App. G	2.3.2	The Draft VITG should provide guidance regarding geostatistical techniques which may be used to characterize similarities and differences between indoor air sample results. Defining the acceptable and the preferred LOE will provide a more robust and relevant guidance document that can decrease the response time when a VC condition is identified.
28	136	App. G	2.3.2	The Draft VTG should provide example scenarios that demonstrate when a VC condition is determined to be inaccurate and unsubstantiated. The Draft VTG should define how an LSRP can document an exceedance of an IARS is caused by conditions other than vapor intrusion.
29	136	App. G	2.3.2	The Draft VTG should provide example scenarios that identify specific actions that are expected by the NJDEP when a VC condition occurs but the site conditions are complex including elevated background air concentrations. We recommend that the NJDEP review the ITRC document, *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios A Supplement to Vapor Intrusion Pathway: A Practical Guideline* , January 2007 as a typical format for describing various scenarios and the actions to address the specified conditions. The NJDEP OMM has utilized the current VITG for almost 3 years, and common scenarios, discrepancies and policy decisions should be described within the next VITG. One scenario should clarify the NJDEP's expectations when the IA concentrations exceed the IARS and are also equal to or greater than subslab air concentrations. One scenario should clarify the NJDEP's expectations when the IA concentrations exceed the IARS for compounds that are not detected in subslab air samples. One scenario should clarify the NJDEP's expectations when a remedial action such as the installation of a subslab ventilation system does not reduce all IA concentrations below the IARS. The NJDEP RAP review team and the Monitoring & Maintenance group should also be interviewed to identify other relevant conditions that have been encountered and the minimum information required by these staff members.

30	136	App. G	2.3.2	The VITG states "A calculator developed by the Department to assist the investigator in the generation of Alternative RAL can be accessed at *http://www.state.nj.us./dep/srp/guidance/rs/index.html* ." Although the NJDEP's calculation tool is referenced 7 times within the VITG, a search of the webpage site does not find the calculator. Stakeholders cannot effectively replicate or validate calculations or evaluate the guidance document without being able to review the calculator function for Alternative RAL. We are requesting the release of the calculators for the Alternative RAL, so the calculator and VITG can be reviewed and commented on appropriately.

Improving Risk-Based Screening at Vapor Intrusion Sites in California

Matthew A. Lahvis and Robert A. Ettinger

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Abstract

Regulatory agencies are increasingly citing the attenuation factor (AF) recommended by the U.S. Environmental Protection Agency to technically underpin chemical specific subsurface vapor and groundwater screening levels for vapor intrusion (VI) investigations. Concerns exist, however, over biases and uncertainties in the data used to derive the AF and general applicability of the AF to certain building types and geographies with differing climatic conditions from those contained in the USEPA database. This study was undertaken to address these concerns and derive a more technically defensible AF for VI screening in California. A database was compiled of more than 8,400 paired indoor and subsurface vapor samples collected at 34 sites (including 4 from the USEPA database) located across California. The database was extensively screened to eliminate poor quality data and vapor samples potentially affected by background (non-VI) sources resulting in a filtered database containing a subset of 643 paired indoor air and subsurface vapor trichloroethylene (TCE) measurements. This TCE database was used to derive an AF that reliably screens buildings with indoor air concentrations above risk-based screening levels. The reliability assessment resulted in an AF = 0.0008, which is over an order of magnitude less than the AF = 0.03 determined by USEPA. This study also found that median

AFs varied by less than an order of magnitude for parameters typically considered important in VI characterization. Application of the AF from this study would minimize unnecessary data collection and allows limited resources to be focused on VI sites with the greatest risk potential.

Introduction

The vapor intrusion (VI) attenuation factor (AF) is a measure of the extent to which vapor concentrations decrease by migration from the subsurface to indoor air and is defined as the ratio of the vapor concentration of a chemical in indoor air (C_{IA}) relative to its concentration in subsurface vapor (C_{SOURCE}):

$$AF = {}^{C_{IA}}/_{C_{SOURCE}}$$

The AF is dependent on numerous factors that affect chemical migration in soil, across building foundations, and within buildings. The AF is used by regulatory agencies to calculate chemical-specific subsurface screening levels (SSSLs) based on indoor air screening levels (IASLs):

$$SSSL = {}^{IASL}/_{AF}$$

AFs and SSSLs are commonly based on either application of the Johnson and Ettinger (1991) model or empirical studies of subsurface and indoor air data (USEPA 2012). The USEPA (2015) recommends an AF = 0.03 for screening purposes, which is increasingly being cited in state regulatory VI guidance documents. This AF is based on a statistical analysis of C_{IA} and C_{SOURCE} data collected at numerous, predominantly chlorinated, VI sites across the US (USEPA 2012). The AF = 0.03 referenced in USEPA guidance represents the 95th percentile of AF values calculated from a database of indoor and subslab vapor concentration data filtered for background sources. Since its publication, the USEPA default AF has been the subject of much debate stemming, in part, from concerns over bias and representativeness if applied at VI sites with temperate climates, slab-on-grade building foundations, and commercial/industrial (C/I) buildings (e.g., office complexes, warehouses, schools, churches, etc.) (Brewer et al. 2014; Yao et al. 2013, 2018; Ettinger et al. 2018). The AF derived in the 2012 USEPA AF study was largely based on data collected from single-family residences with basement foundations (16% unfinished), several of which were located in states, such as Colorado and New York, where VI can be seasonally enhanced by stack effects from heating of indoor air. Both the conservatism and geographic representativeness of the USEPA AF was further drawn into question following an empirical AF study of VI sites in California that reported an order of magnitude lower 95th percentile AF = 0.0026 (Ettinger et al. 2018). The study included a much higher fraction of vapor data collected at C/I buildings and buildings with slab-on-grade and crawl space construction.

Yao et al. (2013) reviewed the USEPA AF database and found little correlation of C_{IA} and C_{SOURCE} data, which can hamper efforts to derive an empirical AF. Some of the poor correlation can be attributed to chemicals with low C_{IA} and C_{SOURCE} which are most susceptible to bias from background (non-VI) sources. Other factors that could challenge empirical AF assessments could include a) uncertainties associated with spatiotemporal variability in C_{IA} and C_{SOURCE} that are discrete in space and sample duration and b) use of concentration rather than flux measurements to characterize VI.

The USEPA attempted to correct for biases potentially attributable to background sources by filtering out vapor data where a) C_{IA} were less than the median of published 90th percentile background levels (USEPA 2011; Dawson and McAlary 2009), b) C_{IA} were greater than C_{SOURCE}

(i.e., instances where AFs were greater than 1), and c) C_{SOURCE} were less than 50x the 90th percentile of background concentrations in indoor air. The C_{SOURCE} filter was used to try and eliminate a bimodal distribution in the AF, however, some bimodality remained after balancing data quality with data retention. These observations highlight fundamental issues that exist with derivation of AFs based on empirical subsurface and indoor air vapor concentration measurements.

As of 2018, nine US states cite USEPA's default AF of 0.03 for VI screening (Eklund et al. 2018). The California Environmental Protection Agency (CalEPA) is currently proposing to adopt USEPAs AF, which represents a substantial increase in the AF from the values (0.002 for residential buildings; 0.001 for commercial/industrial buildings) recommended in previous state guidance (DTSC 2011, SFBRWQCB 2016). If adopted, the AF has the potential to "screen in" many new sites in California which would greatly increase the number of instances where indoor air sampling is required by regulatory agencies. Further work is therefore needed to understand the impact of the change, especially given the concerns with the USEPA AF expressed previously and the possible impacts on state and financial resources and building occupants. This study represents an extension of the California empirical AF study by Ettinger et al. (2018) and includes additional data, alternative data analysis, and more detailed assessment of variables that potentially affect the AF.

California VI Database

The California VI database was populated with data manually extracted from site investigation reports, including several made publicly available via CalEPA's online Geotracker Database (https://geotracker.waterboards.ca.gov/). General site information and characteristics of the database are summarized in **Table 1**. In total, the database consists of 8415 paired subsurface (subslab and soil gas) and indoor air vapor concentration measurements collected from 495 buildings located at 34 sites. The vapor data pairs were defined for each individual indoor air and subsurface vapor sample collected at a given building during a particular sampling event. As such, one indoor air sample may have been paired with multiple subsurface vapor samples or one subsurface vapor sample may have been paired with multiple indoor air samples. The VI sites in the database were predominantly located in the metropolitan areas of Los Angeles, San Francisco, and San Diego. The database contains vapor concentration data for 33 chemicals, most of which are trichloroethylene (TCE) (39%) and tetrachloroethylene (PCE) (23%). Overall, petroleum hydrocarbons (benzene, alkylbenzenes, alkanes, and naphthalene) constituted only a small percentage (7%) of total population of unfiltered data pairs. The VI data were collected primarily from residential buildings (52%), commercial (24%) and industrial properties (16%), with a smaller contribution from military bases (5%) and schools (2%). The number of residential sites (10) was less than one-half the number of C/I sites (22), indicating a higher frequency of vapor sampling at residential versus C/I sites. The geographic distribution of residential data was relatively limited with 98% of the residential data from 6 sites located in Los Angeles and Orange Counties. Most of the data in the California database were from buildings with slab-on-grade foundations (75%); the remaining 25% of buildings had crawl space foundations, which all included soil-gas sampling. The foundation types for residential buildings was more evenly split between crawl space (47%) and slab-on-grade (53%) construction. Only

Table 1. Summary of general site information in the California VI database.

City	Building Type/Land Use	Primary VOC	# of Buildings	Subslab Samples	Soil Gas Samples
El Cajon	Residential	PCE, TCE, 1,1-DCE	20		X
Newport Beach	Residential	TCE	43		X
Burbank	Residential - Single Family	PCE, TCE	5	X	X
Carson	Residential - Single Family	Petroleum, PCE, TCE	253	X	
Los Angeles	Residential - Single Family	PCE, TCE	17		X
Puente Valley	Residential - Single Family	PCE, TCE, Other	14	X	X
Los Angeles	Residential - Multi-Family	PCE, TCE	9	X	X
Alameda	Commercial	PCE, TCE	3	X	
Bell Gardens	Commercial	Radon	2	X	
Emeryville	Commercial	PCE	5		X
Oakland	Commercial	CVOCs	1	X	
San Diego	Commercial	PCE, TCE	1	X	X
San Mateo	Commercial	PCE, TCE	1	X	X
Santa Clara	Commercial	PCE, TCE	6	X	
Santa Clara	Commercial	PCE	1		
Torrance	Commercial	TCE, PCE	1		X
Davis	Commercial	PCE	4	X	
Brisbane	Industrial	PCE, TCE, Other	1	X	
Compton	Industrial	TCE, PCE	1		X
Los Angeles	Industrial	PCE, TCE	1	X	
Los Angeles	Industrial	TCE, PCE	1	X	X
Orange County	Industrial	TCE, PCE	1	X	X
Ontario	Industrial	TCE, PCE	1		X
Santa Fe Springs	Industrial	PCE, TCE, Other	2	X	
San Leandro	Industrial	PCE	1	X	
South San Francisco	Industrial	PCE, TCE	2	X	X
South San Francisco	Industrial	TCE	1		X
El Cajon	Commercial/Industrial	CVOCs	4	X	
Edwards	Military	PCE, TCE	13	X	X
San Diego	Military	TCE	13	X	
El Cajon	School	TCE	8		X
Los Angeles	School	PCE, TCE	13	X	X
Alameda*	Commercial	Petroleum	1	X	X
Mountain View *	Residential	TCE	3	X	X
Mountain View *	Residential	TCE	5		X
Mountain View *	Residential	TCE, PCE	8	X	

* included in USEPA (2012) VI Database

one site had a building with a basement foundation which was eventually screened out based on the filtering process presented later. In general, the database is believed to reflect a representative population and distribution of VI sites and building types in California.

The database contains information on the following variables that are commonly believed to directly or indirectly affect the AF:

- current land use (e.g., residential, commercial, industrial, school);
- building type/use: (e.g., retail, manufacturing, storage, office, warehouse, school; single-family homes, multi-family buildings;
- building foundation type (slab on grade, basement, crawl space);
- building size (square footage);
- chemical name;
- vapor concentration (indoor air, outdoor/ambient air, subsurface vapor – subslab or soil gas) and detection limits;
- subsurface sample type (soil gas, subslab);
- soil-gas sample depth (feet below ground surface – ft bgs);
- predominant vadose zone soil type;
- surrounding surface cover (pavement, open ground);
- sampling dates (indoor, outdoor/ambient, and subsurface vapor) and indoor air sample duration (8, 12, or 24 hour);
- subsurface sample distance relative to indoor air and building perimeter;
- heating, ventilation, and air-condition (HVAC) operation during sampling (on, off, not reported); and

- quality assurance/quality control (QA/QC) issues and measures (leak testing, vacuum loss, tracer identification, preferential pathway, background source, other).

The data entered into the database were extensively reviewed to assess data quality. QA/QC measures included reviews of site investigation reports, site plans, vapor sample collection methods and analysis, data quality testing (e.g., pneumatic and tracer testing, purging procedures), and broad consistency with the VI conceptual model. Suspect data associated with unacceptable QA/QC, sample methods, and presence or suspected presence of preferential pathways (sumps, elevators) and indoor air sources were flagged and eliminated from further analysis. This process reduced the total number of vapor data pairs from 8415 to 7891.

The database was further filtered to remove data assumed to be of lesser quality or potentially influenced by background (non-VI) chemical sources (see **Table 2**). Filters A - E are consistent with those applied by USEPA (2012); the key differences being the elimination of vapor data pairs where C_{IA} are less than chemical concentrations in outdoor air (C_{OA}) and C_{SOURCE} less than 500x the median of 90th percentile of background indoor air concentrations (C_{BGRD}) reported in the literature. The C_{OA} filter was intended to exclude low-concentration C_{IA} data with greater likelihood of bias from indoor-outdoor air exchange, recognizing that the bias could not be fully eliminated. The 500x C_{BGRD} multiplier resulted in the most normally distributed C_{SOURCE} data (see **Figure 1**) and the exclusion of lower concentration C_{SOURCE} data (i.e., higher AF values) with greater likelihood of being biased by background sources and other confounding factors. The 500x multiplier is an order of magnitude higher than the 50x C_{BGRD} filter applied by USEPA (2012), yet similar to the 300x C_{BGRD} multiplier used by Song (2011) in an evaluation of

Table 2. Database filters to account for data quality and background (non-VI) chemical sources.

FILTER	ALL CHEMICALS		TCE ONLY	
	# OF VAPOR DATA PAIRS ELIMINATED	TOTAL REMAINING DATA PAIRS	# OF VAPOR DATA PAIRS ELIMINATED	TOTAL REMAINING DATA PAIRS
A. C_{IA} < analytical detection and reporting levels)	3272	4619	1150	1859
B. C_{IA} < median of 90th percentile of residential background C_{IA} reported in literature including chemicals with unreported or unknown background C_{IA} data	3357	1262	959	900
C. C_{IA} greater than C_{SOURCE} concentrations (i.e., AF >= 1)	30	1232	14	886
D. C_{IA} < reported C_{OA}	13	1219	11	875
E. C_{SOURCE} < 500x C_{BGRD} including U-qualified data	138	1081	52	823
F. C_{SOURCE} < analytical detection or reporting levels	94	987	14	809
G. paired C_{IA} and C_{SOURCE} samples reported to be more than 92 days (~3 months) apart	95	892	63	746
H. paired C_{IA} and C_{SOURCE} samples reported to be more than 100 feet apart (including C_{IA} samples collected from 2nd floors of buildings)	90	802	89	657
I. soil-gas data collected more than 30 ft bgs	14	788	14	643

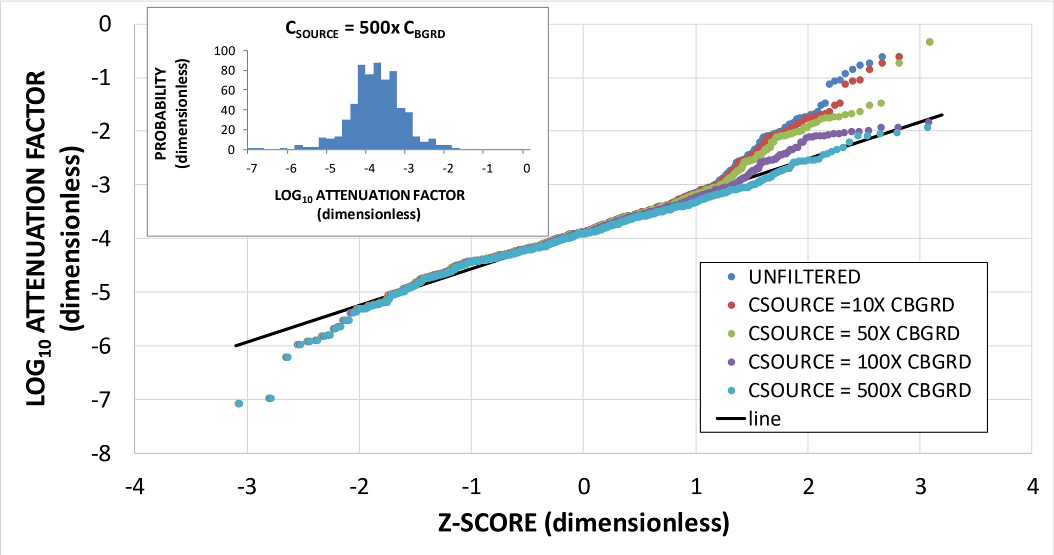


Figure 1. Cumulative probability plots summarizing empirical attenuation factors determined from the filtered TCE database associated with various levels of subsurface chemical vapor concentrations (C_{SOURCE}) screening based on 10x, 50x, 100x, and 500x multipliers of the 90th percentile of background chemical concentrations in indoor air (C_{BGRD}). The histogram inset illustrates the distribution of empirical AF for the most normal distribution of C_{SOURCE} data which was achieved by filtering out C_{SOURCE} less than 500x C_{BGRD}. The z-score indicates the number of standard deviations a given AF value is above or below the mean of the AF distribution.

USEPA's 2008 empirical AF database. The effect on the C_{SOURCE} filtering and the coupling of subslab and soil- gas data were later shown to have a negligible effect on the TCE data used in the AF determination (see Results and Discussion). As indicated, the vast majority (6629 data pairs = 84%) of vapor data pairs are screened by the application of Filters A and B. Although the intent of these filters was to reduce bias in the AF associated with low C_{IA} data generated from background (non-VI) chemical sources, these filters have the potential to bias the AF high because of the elimination of low C_{IA} rightly attributable to VI. The USEPA (2012) attempted to retain some of the low C_{IA} (non-detect) data by applying the Kaplan-Meier method (Kaplan and Meier 1958). The Kaplan-Meier method was not applied in this study because the 95th percentile AFs calculated using TCE only data were essentially equivalent regardless of whether non-detect data were factored in (see Results and Discussion – Figure 6a). The remaining filters (i.e., Filters

D and G-I) were added to improve the overall quality of the empirical data yet were ultimately shown to be inconsequential given the limited sensitivity of the AF to these factors (see Results and Discussion).

The application of the data quality and background vapor concentration filters resulted in a dataset consisting of 788 C_{IA} and C_{SOURCE} vapor data pairs chemically distributed as follows: TCE (643 data pairs = 82% of population); PCE (138 data pairs = 18% of population), and 1,1-dichloroethylene (1,1-DCE) (7 data pairs = < 1% of population). A summary of the database as a function of building type (and broadly categorized as “non-residential” -- commercial, industrial, military, and school; and “residential”), chemical, and sample type is provided in **Table 3**.

Table 3. Paired vapor data populations as a function of building type, chemical, and sample type.

BUILDING TYPE	CHEMICAL			BUILDING-TYPE DESIGNATION	SUBSLAB SAMPLE POPULATION*	SOIL-GAS SAMPLE POPULATION*
	TCE	PCE	ALL			
Commercial	36	47	83	NON-RESIDENTIAL	192	127
Industrial	91	68	160			
Military	50	0	50			
School	6	20	26			
SUBTOTAL	183	135	319			
Residential	460	3	469	RESIDENTIAL	4	465
TOTAL	**643**	**138**	**788**		**196**	**592**

* All chemicals

The filtered database was used to both derive an empirical AF and assess the effects of background indoor air concentrations and key variables on the AF. Only TCE vapor data were ultimately used in the AF derivation to reduce the potential for chemical-specific variability and eliminate chemicals, in the case of PCE, which were later shown by a sensitivity analysis to be more affected by non-VI sources (see Results and Discussion). In comparison, the final TCE database used to derive the empirical AF is larger than the USEPA (2012) database in both sample population (643 versus 431 vapor data pairs) and site count (19 versus 12). Approximately 72% (N = 460) and 28% (N = 183) of the TCE vapor data pairs were from residential and non-residential building types, respectively. Less than (4/460) 1% of the residential vapor samples were collected subslab. The filtered TCE database included a relatively high percentage (465/643 = 71%) of exterior soil-gas vapor data pairs that were not factored into the derivation of the AF by USEPA, because they were found the soil-gas data to be non-representative based on a calculated 95th percentile AF = 0.3 (USEPA 2012). The inclusion of a large percentage of soil-gas data, including the small population of subslab samples from residential buildings, and the elimination of chemicals other than TCE represent other key contrasts between this and the USEPA study in the AF derivation. The Results and Discussion section that follows describes the use of descriptive statistics (box and whisker plots) to assess the effects of all background C_{IA} and C_{SOURCE} filtering and key variables, such as sample type (soil gas versus subslab), on the AF.

Results and Discussion

Calculated Empirical AFs

C_{IA} are relatively independent of C_{SOURCE}, especially below 10,000 μg/m^3 (**Figure 2**). The lower bound in C_{IA} (0.01 – 0.1 μg/m^3) largely coincides with analytical detection limits for various VOCs in indoor air. The upper bound, generally marked by C_{IA} ~ 20 μg/m^3, implies there may be certain factors or adsorption or reaction processes affecting maximum C_{IA} generated from subsurface or indoor air sources. This finding is similar to the that of Yao et al. (2013), in their review of the

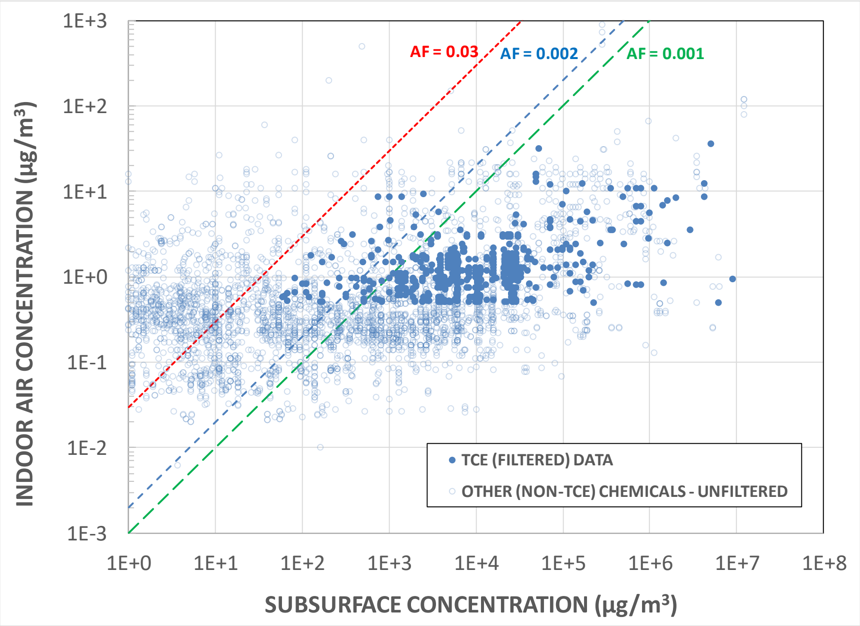


Figure 2. Concentrations of all chemicals in indoor air (C_{IA}) plotted as a function of subsurface vapor concentrations (C_{SOURCE}) for filtered TCE data (full circles) and all other chemicals (open circles) contained in the unfiltered California database. The vapor concentration data are plotted relative to the USEPA recommended AF = 0.03 and AFs previously applied by CalEPA for residential (AF = 0.002) and C/I (AF = 0.001) buildings.

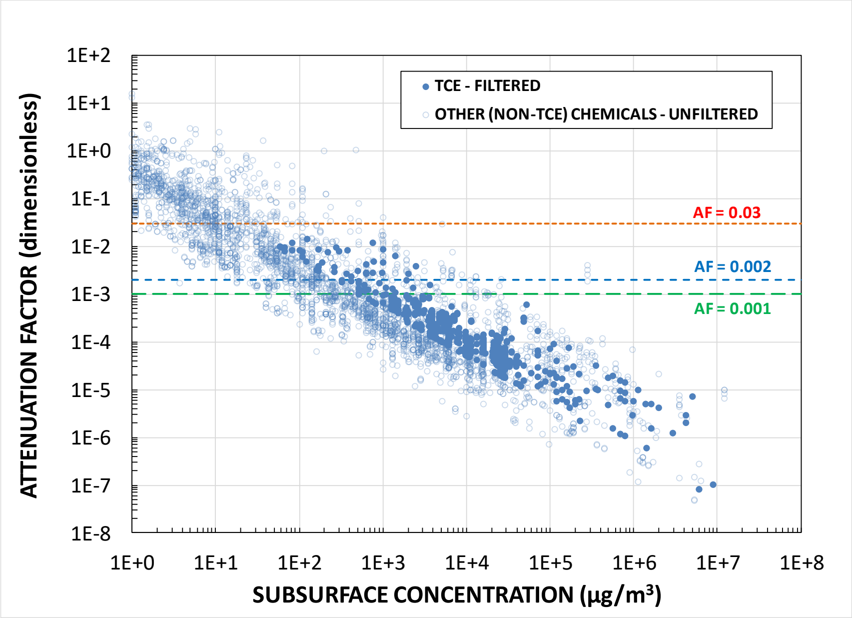


Figure 3. Empirical attenuation factors (AFs) plotted as a function of subsurface vapor concentration (C_{SOURCE}) for the filtered TCE data (full circles) and all other chemicals (open circles) contained in the unfiltered California database. The vapor concentration data are plotted relative to the USEPA recommended AF = 0.03 and AFs previously applied by CalEPA for residential (AF = 0.002) and C/I (AF = 0.001) buildings.

USEPA (2012) AF database. Likewise, the poor correlation between C_{IA} and C_{SOURCE} results in AFs that decrease with increasing C_{SOURCE}, which is expected based on the observed ranges of C_{IA} and C_{SOURCE} data (**Figure 3**). These findings, again, highlight the uncertainties in empirical AF assessments based solely on discrete indoor air and subsurface vapor concentration measurements.

The filtered database was nevertheless used to derive AFs for TCE and PCE. The 95th percentile AF for TCE based on the filtered database is 0.0013. This AF is approximately one-half the 95th percentile for PCE (0.0025). Median AFs for TCE and PCE are essentially equivalent (0.00012) and less than 95th percentiles. These empirical AFs f magnitude, which was also observed in the USEPA (2012) study. These empirical AFs are approximately an order of magnitude less than the AF values reported in USEPA (2012). The effect of various factors on the AF distributions is discussed in greater detail in a subsequent section (see Factors that Affect the AF).

Reliability Assessment

Following the approach used by USEPA (2015), an assessment was conducted to assess the reliability of the AF as a VI screening tool. In particular, reliability was defined by the percentage of times the AF would "correctly" or "incorrectly" identify potential VI risks when applied to the filtered TCE database. Correct assessments were denoted by:

a) True Positives: C_{SOURCE} > SSSL <u>and</u> C_{IA} > IASL; and

b) True Negatives: C_{SOURCE} < SSSL <u>and</u> C_{IA} < IASL.

Incorrect assessments were denoted by:

a) False Negatives: $C_{SOURCE} < \text{SSSL}$ and $C_{IA} > \text{IASL}$; and

b) False Positives: $C_{SOURCE} > \text{SSSL}$ and $C_{IA} < \text{IASL}$.

An excessively low AF will trigger a disproportionate number of false negatives (i.e., fail to identify instances where C_{IA} is above the IASL and further investigation is warranted). Conversely, an excessively high AF will generate an overabundance of false positives (i.e., unnecessary investigations in buildings where C_{IA} is below the IASL).

The AF reliability methodology was used by USEPA to support the AF = 0.03 value based on the 95th percentile of calculated AFs from their filtered database (USEPA 2015). In this study, the reliability assessment is favored over the 95th percentile of calculated AFs primarily because a) the C_{IA} and C_{SOURCE} data are poorly correlated and b) the ultimate goal of this study is to derive an AF that reliably predicts C_{IA} above IASLs where C_{SOURCE} exceeds SSSLs. AF reliability was assessed for the filtered TCE database using the following relation:

$$\frac{total\ \#\ of\ true\ positives}{(total\ \#\ of\ true\ positives + total\ \#\ of\ false\ negatives)}\ or\ \frac{total\ \#\ of\ true\ positives}{total\ \#\ of\ C_{IA} > IASLs} = 95\%$$

which represents the threshold where C_{SOURCE} exceed SSSLs in 95% of instances where C_{IA} exceed IASLs. The 95% reliability criterion described above was believed to be an improvement over the one undertaken by USEPA (2015) because this analysis places greater emphasis on locations where C_{IA} exceed IASLs. The TCE IASLs used in this study were those currently applied in California for residential (0.48 µg/m^3) and C/I (3.0 µg/m^3) buildings; SSSLs were calculated by dividing the IASLs by the variable AF.

The 95th percentile reliability criterion corresponds to AFs = 0.0004, 0.003, and 0.0008 for residential, C/I and all building types, respectively (**Figure 4**). The higher AF for C/I buildings is likely skewed by a very small false negative population (3 out of 48 total C/I data samples). Of note, minor changes in the distribution of TCE vapor data have relatively little effect on the AF determined for the 95th percentile criterion. The distribution of true positives, false negatives, false positives, and true negatives associated with an AF = 0.0008 is illustrated in **Figure 5** and summarized in **Table 4**. For comparison**,** this AF is approximately one-half of the AF determined from the reliability analysis using subslab only TCE data (AF = 0.0017). Application of the AF = 0.0008 to the TCE database versus the USEPA AF = 0.03 increases the

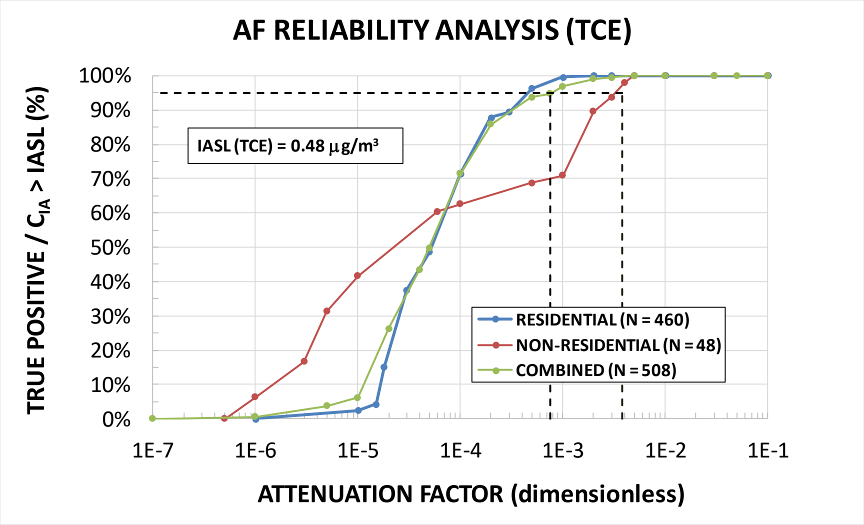


Figure 4. Probability distribution of attenuation factors (AFs) where C_{IA} > IASL and C_{SOURCE} > SSSL ("true positives") relative to the total population of C_{IA} for filtered TCE data from the California database. The distributions are plotted for the vapor data collected from residential, non-residential (commercial, industrial, military, and school), and combined (both) building types.

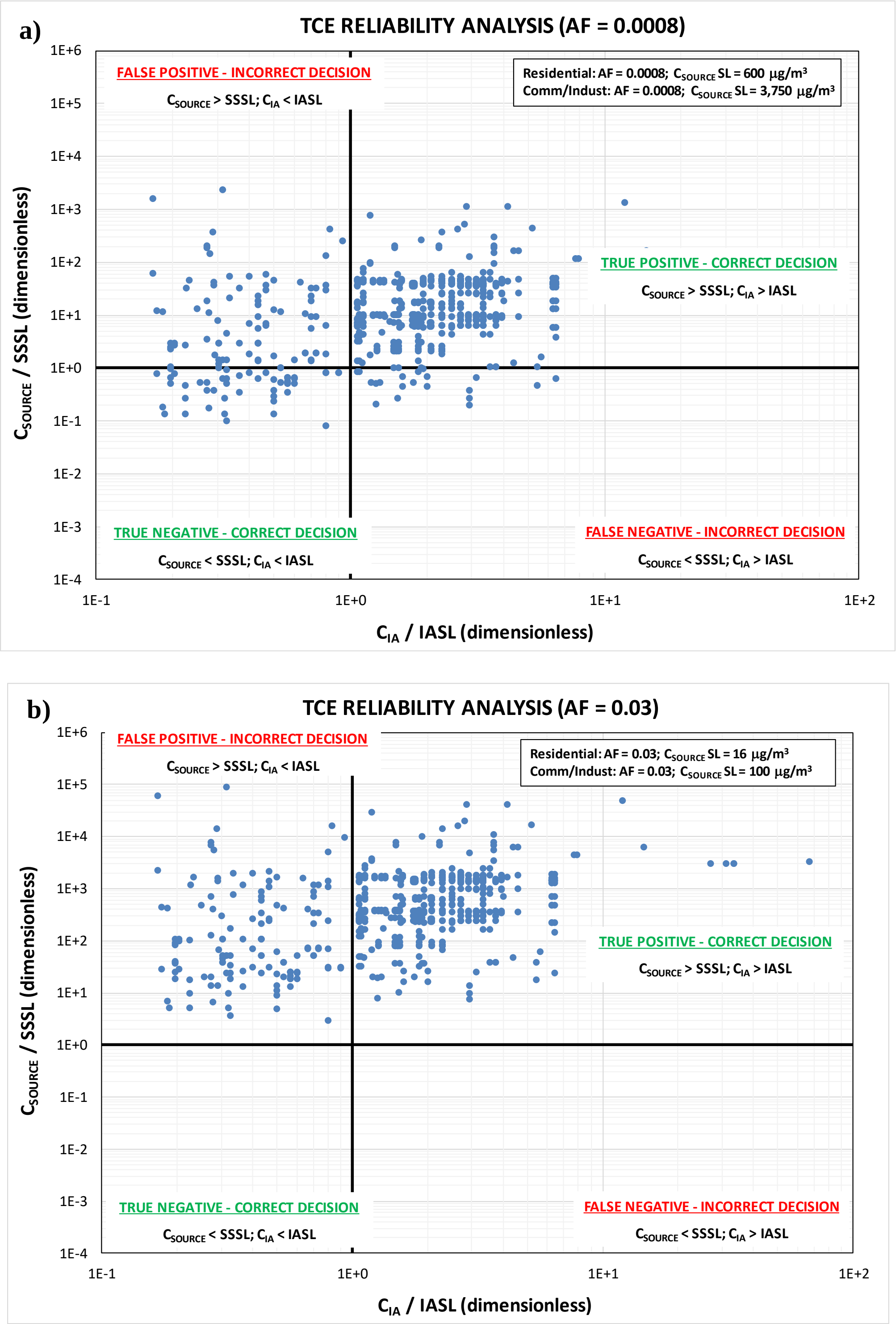


Figure 5. Reliability analysis showing distribution of C_{SOURCE} > SSSL versus C_{IA} > IASL for the TCE filtered data. The quadrants indicate populations of vapor concentration data associated with correct decisions ("true positives" and "true negatives") and incorrect decisions ("false positives" and "false negatives") that result from application of a) the empirical AF derived from this study (AF = 0.0008) and b) the USEPA default AF (AF = 0.03).

Table 4. A comparison of reliability analysis criteria for the various empirical AFs.

DATA SET	EMPIRICAL AF	RELIABILITY CRITERION			
		TRUE POSITIVES	FALSE NEGATIVES	FALSE POSITIVES	TRUE NEGATIVES
TCE: ALL (N = 643)	0.0008	481 (75%)	27 (4%)	81 (13%)	54 (8%)
TCE: SUBSLAB ONLY (N = 147)	0.0017	33 (22%)	2 (1%)	98 (67%)	14 (10%)
TCE: SOIL GAS ONLY (N = 496)	0.0006	451 (91%)	22 (4%)	16 (3%)	7 (1%)
TCE ALL: USEPA AF (N = 643)	0.03	508 (79%)	0 (0%)	135 (21%)	0 (0%)

number of true positives by over 25% (correct decisions) while maintaining the number of false negatives below 5%. The application of the AF = 0.0008 to the filtered TCE dataset also a) decreases the number of "false positives" or instances where indoor air samples may be collected unnecessarily by 8% and b) increases the number of true negatives or instances where indoor air sampling was not necessary by 8% compared to the USEPA AF = 0.03. As indicated, no C_{SOURCE} were below SSSLs of 16 (residential) or 100 (C/I) $\mu g/m^3$ (i.e., no false negatives or true negatives) result from application of the USEPA AF = 0.03 to the TCE filtered database (See **Figure 5b** and **Table 4**). Lastly, the AF = 0.0008 derived from the reliability assessment is slightly lower than the 95th percentile of calculated AFs derived from the filtered TCE vapor dataset (AF = 0.0013) (see Table 4), the 95th percentile AF derived from the initial evaluation of empirical California data (AF = 0.0026) (Ettinger et al. 2018) and the values for residential (AF = 0.002) and C/I (AF = 0.001) previously recommended in California guidance (DTSC 2011; SFBRWQCB 2016).

Factors Affecting the AF

General sensitivities of the AF to background vapor concentration data filtering and key factors contained in the filtered database was assessed using descriptive statistics (see **Table 5**) and box-and-whisker plots (see **Figures 6 and 7**). The box-and-whisker plots graphically illustrate the distribution of the AF population (N) through lower (lower box boundary) and upper (upper box boundary) quartiles, 95th percentiles (open circles), means (cross), medians (line within box), and minimum (lower whisker) and maximum (upper whisker) values.

As indicated, 95th percentile and overall variance of AFs are generally less for TCE than PCE even though the AF is expected to be independent of chemical type. The differences can be explained, in part, by the higher likelihood of encountering background sources of PCE in indoor air (Dawson and McAlary 2009; USEPA 2011) and the high percentage of PCE data collected at non-residential sites (98%) (see **Table 3**) where C_{IA} and C_{SOURCE} vapor concentrations are more variable. The effect of C_{IA} filtering and elimination of indoor air data potentially affected by background sources, however, has relatively little effect on the 95th percentile and variance of AFs for both TCE and PCE (see **Figure 6a**). Examination of the AF distribution plots with and without non-detected results included in the analysis indicates that efforts to retain more low-concentration C_{IA} data for empirical AF determinations using Kaplan-Meier statistics would have had little overall impact on the AF. The 95th percentile AFs are more affected by C_{SOURCE} filtering and the elimination of low-concentration source vapor data (see **Figure 6b**) that were less log-normally distributed (see **Figure 1**). C_{SOURCE} filtering has lesser effect on the AF distributions for TCE than PCE, which can be explained by the elimination of a smaller percentage of low-concentration vapor sources for TCE (40/683 = 6%) than PCE (49/187 = 26%). Overall, TCE vapor data appears to be more suitable for VI screening than PCE and other

Table 5. Distribution of AFs as a function of select database variables.

CHEM-ICAL	CATEGORY	VARIABLE	PAIRED VAPOR DATA POPU-LATION	95th %ILE	90th %ILE	50th %ILE
TCE	**FILTERED DATABASE**	**All**	643	0.0013	0.00073	0.00012
	C_{IA} FILTER – PERCENTILES FROM BACKGROUND STUDIES ND = Non-Detect DLs = Detection Levels RLs = Reporting Levels	NDs at DLs & RLs	1371	0.0013	0.00070	0.000088
		No NDs	908	0.0010	0.00065	0.00011
		50th %ile	764	0.0012	0.00071	0.00011
		75th %ile	720	0.0013	0.00074	0.00012
		Median 90th %iles	643	0.0013	0.00073	0.00012
	C_{SOURCE} FILTER – MULTIPLIERS of BACKGROUND C_{IA}	No Filter	683	0.0080	0.0016	0.00013
		50x C_{IA}	675	0.0046	0.0012	0.00013
		100x C_{IA}	661	0.0028	0.00088	0.00013
		500x C_{IA}	643	0.0013	0.00073	0.00012
	BUILDING TYPE	Residential	460	0.00081	0.00053	0.00012
		Commercial	36	0.0021	0.0016	0.00068
		Industrial	91	0.0023	0.00080	0.000037
		Military	50	0.0022	0.00088	0.00012
		School	6	0.0035	0.0033	0.0021
	FOUNDATION TYPE	Slab	623	0.0012	0.00071	0.00012
		Crawl Space	20	0.0029	0.0029	0.00029
	SOIL-GAS SAMPLING DEPTH	x < 10 ft	278	0.0018	0.00084	0.00025
		x >= 10 ft	218	0.00030	0.00018	0.000061
	SOIL TYPE	Sands/Gravels	73	0.0029	0.0022	0.00031
		Silts/Clays	493	0.00065	0.00046	0.00012
	SURROUNDING SURFACE COVER	Pavement	496	0.00081	0.00054	0.00012
		Open Ground	36	0.0029	0.0023	0.00061
	HVAC OPERATION	On	72	0.00049	0.00031	0.000048
		Off/None	50	0.0051	0.0028	0.00068
	SAMPLE TYPE	Soil Gas	496	0.0010	0.00058	0.00012
		Subslab	147	0.0024	0.0012	0.00012
	DISTANCE BETWEEN SUBSURFACE SAMPLE AND BUILDING PERIMETER	Subslab: x ≤ 10 ft	7	0.0057	0.0034	0.0000029
		Subslab: 10 < x ≤ 20 ft	27	0.00051	0.00043	0.000046
		Subslab: 20 < x ≤ 30 ft	25	0.00078	0.00070	0.000058
		Subslab: x > 30 ft	61	0.0016	0.0011	0.000063
		Soil Gas: x ≤ 30 ft	195	0.00083	0.00058	0.00013
		Soil Gas: 30 < x ≤ 60 ft	167	0.0016	0.00048	0.000096
		Soil Gas: x > 60 ft	121	0.00084	0.00038	0.00013
	DISTANCE BETWEEN INDOOR AIR & SUBSURFACE VAPOR SAMPLE LOCATION	x < 25 ft	84	0.0027	0.00094	0.00010
		25 ≤ x 50 ft	177	0.00081	0.00057	0.00011
		x ≥ 50 ft	348	0.0012	0.00063	0.00012
	TIME BETWEEN INDOOR AIR AND SUBSRRCE VAPOR SAMPLING	t < 7 days	106	0.0059	0.0033	0.00018
		7 ≤ t < 30 days	208	0.00096	0.00068	0.00010
		t ≥ 30 days	325	0.00071	0.00053	0.00012
PCE	**FILTERED DATABASE**	**All**	138	0.0025	0.0022	0.00012
	BUILDING TYPE	Residential	3	0.0022	0.0021	0.0017
		Commercial	47	0.0030	0.0024	0.00016
		Industrial	68	0.0025	0.0018	0.00018
		Military	0	--	--	--
		School	20	0.00057	0.00017	0.000070
ALL VOCs	**FILTERED DATABASE**	**All**	788	0.0018	0.00090	0.00012
	BUILDING TYPE	Residential	469	0.00084	0.00057	0.00012
		Commercial	83	0.0027	0.0023	0.00040
		Industrial	160	0.0025	0.0015	0.000052
		Military	50	0.0022	0.00088	0.00012
		School	26	0.0028	0.0021	0.000089

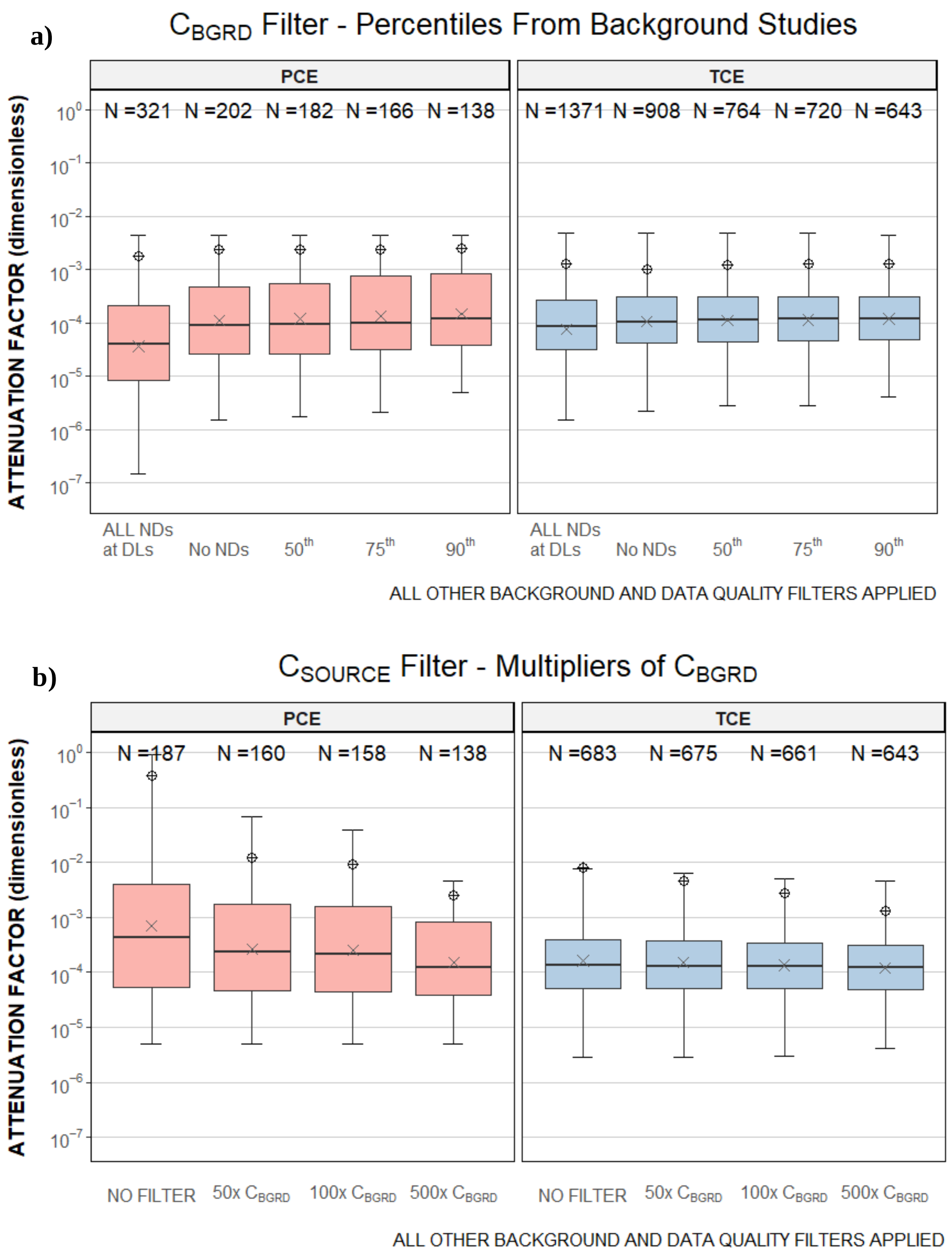
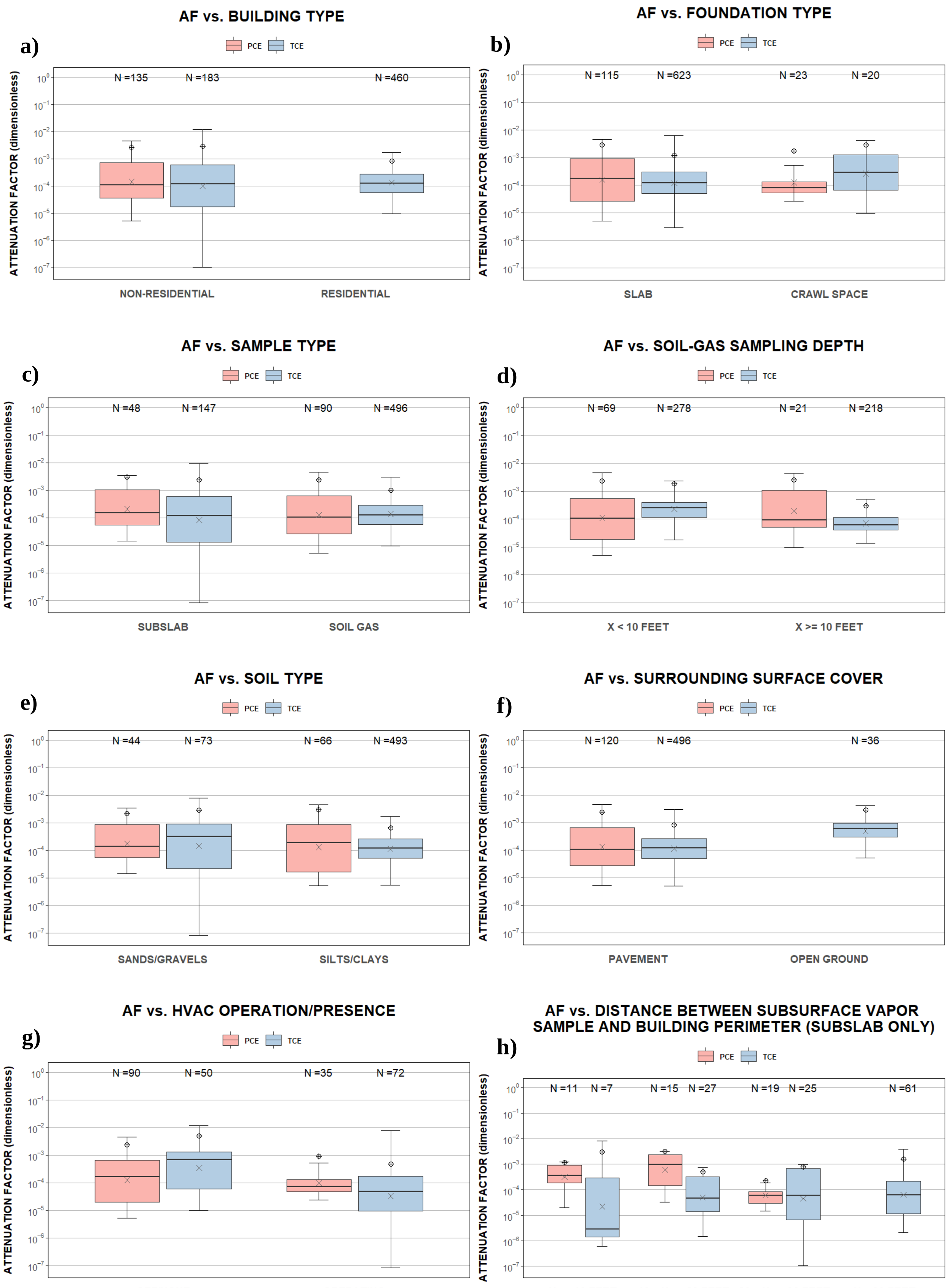


Figure 6. Statistical distributions of empirical attenuation factors (AF) plotted as a function of background vapor concentration filters for a) C_{IA} based on 50th, 75th percentiles, and 90th percentiles of median background chemical concentrations in indoor air studies (McAlary and Dawson 2009; USEPA 2011), and b) C_{SOURCE} based on no filter (i.e., 1x), 50x, 100x, and 500x multipliers of C_{IA} for the specified vapor data pair. N represents the sample population size.


a)
AF vs. BUILDING TYPE
PCE
TCE
ATTENUATION FACTOR (dimensionless)
N =135
N =183
N =460
NON-RESIDENTIAL
RESIDENTIAL
b)
AF vs. FOUNDATION TYPE
N =115
N =623
N =23
N =20
SLAB
CRAWL SPACE
c)
AF vs. SAMPLE TYPE
N =48
N =147
N =90
N =496
SUBSLAB
SOIL GAS
d)
AF vs. SOIL-GAS SAMPLING DEPTH
N =69
N =278
N =21
N =218
X < 10 FEET
X >= 10 FEET
e)
AF vs. SOIL TYPE
N =44
N =73
N =66
N =493
SANDS/GRAVELS
SILTS/CLAYS
f)
AF vs. SURROUNDING SURFACE COVER
N =120
N =496
N =36
PAVEMENT
OPEN GROUND
g)
AF vs. HVAC OPERATION/PRESENCE
N =90
N =50
N =35
N =72
OFF/NONE
OPERATING
h)
AF vs. DISTANCE BETWEEN SUBSURFACE VAPOR SAMPLE AND BUILDING PERIMETER (SUBSLAB ONLY)
N =11
N =7
N =15
N =27
N =19
N =25
N =61
X <= 10 FEET
10 < X <= 20 FEET
20 < X <= 30 FEET
X > 30 FEET
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

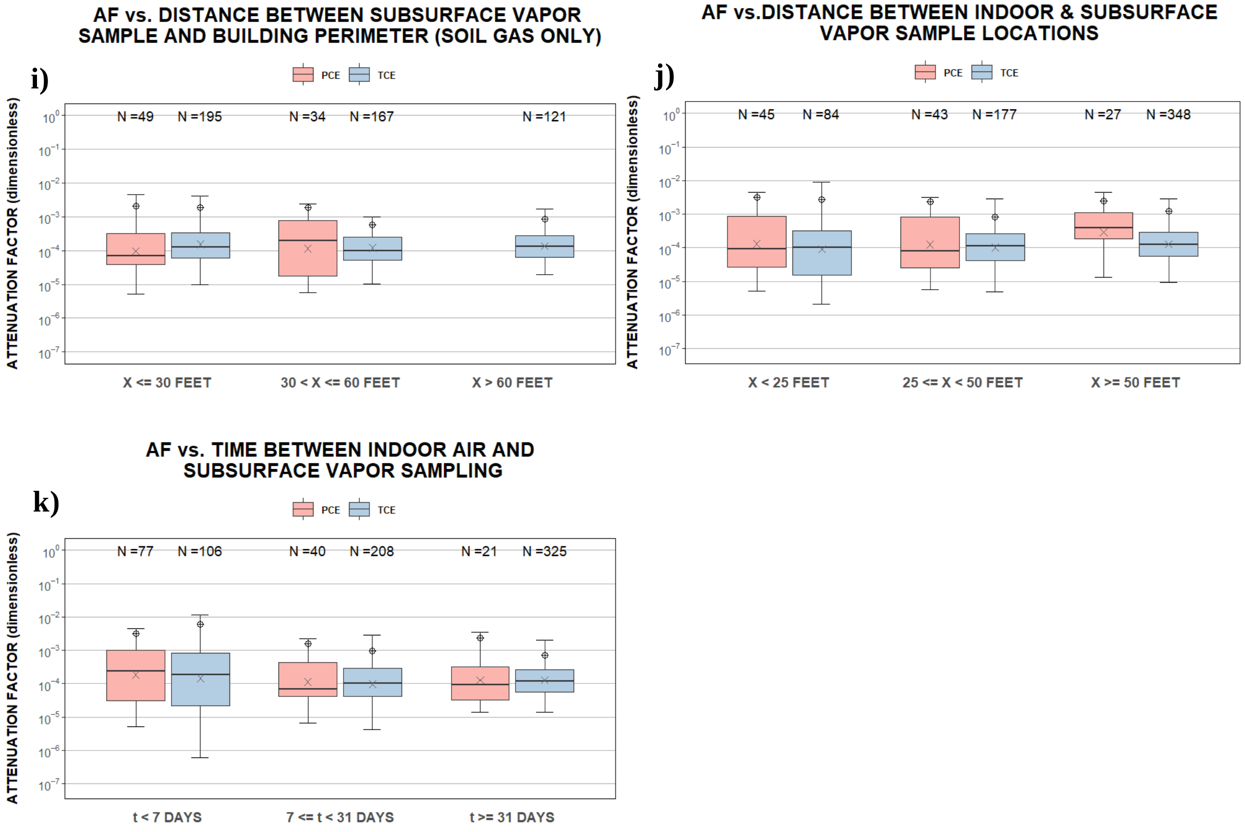


Figure 7. Statistical distributions of attenuation factors (AF) data calculated from the filtered database as a function of a) building type, b) foundation type, c) subsurface vapor sample type, d) subsurface soil type, e) soil-gas sample depth, f) HVAC operation, g) land surface cover surrounding building, h) subsurface sample – building perimeter offset distance (subslab data), i) subsurface sample – building perimeter offset distance (soil-gas data), j) distance between indoor air and subsurface vapor sample locations, and k) time between indoor air and subsurface vapor sampling. N represents the sample population size.

chemicals with low vapor source concentrations that are likely to be eliminated by C_{IA} and C_{SOURCE} filtering.

As shown in **Figure 7**, median AFs for TCE generally vary within an order of magnitude for most of the factors evaluated. The distribution of AFs was generally more sensitive to:

- Building type (**Figure 7a**): Although there were insufficient data to assess the distribution of AFs for PCE in residential buildings (N = 3), the evaluation indicates AFs are generally more variable for non-residential than residential buildings. The median values for TCE residential (0.00012) and non-residential (0.00012) are equal, but the 95th percentile AF value for residential (0.00081) is approximately 3.5 times less than the non-residential value (0.0029). This difference is attributed to a much higher relative percentage of subslab (78%) versus soil-gas (22%) samples, greater variability in source locations (e.g., groundwater versus soil source immediately beneath the building foundation in a portion of the building), and greater likelihood of encountering wider ranges in C_{IA} and C_{SOURCE}, HVAC operation, and indoor air exchange rates in non-residential buildings.
- Foundation type (**Figure 7b**): AFs determined from soil-gas data at buildings with crawl space are approximately 2.5 times higher than those for the slab on grade buildings. This finding implies that C_{IA} may be more sensitive to vapor transport through the vadose zone than across the building foundation. Note that this evaluation of soil gas to indoor air AFs is different from the USEPA (2012) assessment of crawl space to indoor air AFs. Our study did not include an evaluation of the crawl space to indoor air AFs, because crawl space data are typically not used for initial screening at VI sites.
- Sample type (**Figure 7c**): The 95th percentile AF determined from subslab TCE data (0.0024) is approximately 2x higher than soil gas (0.0010). This finding is consistent with the general VI conceptual model which assumes lower soil gas AFs due to mass flux limitations associated with diffusion through the vadose zone.

- Soil type (**Figure 7d**): Median and 95th percentile AFs for TCE are approximately 2.5 – 4.5 times less for the lower permeability soil types (silts/clays). This difference is not reflected in the PCE data which may be masked by the greater relative variance in AFs for PCE.
- Soil gas sample depth (**Figure 7e**): Median and 95th percentile AFs based on shallow (< 10 ft bgs) TCE soil-gas data are approximately 4 – 6 times higher than those based on deeper (≥ 10 ft bgs) soil gas data. These findings are consistent with the VI conceptual model with a vapor source at depth (e.g., groundwater) and mass transport limited by diffusion through the vadose zone.
- HVAC operation (**Figure 7f**): Median and 95th percentile AFs for TCE are approximately 10 - 14x less for operating versus non-operating/non-existing HVAC systems. This difference may indicate that these systems act to reduce or disperse chemical concentrations in indoor air. However, AFs based on data collected while the HVAC system is not in operation may not be representative of those during building occupation and thus inappropriate for risk-based decision making.
- Surface cover (**Figure 7g**): AFs based on TCE data are generally higher for buildings surrounded by open ground rather than pavement. The basis for this is not well understood and may simply reflect the relatively limited population (36 samples) of vapor data collected at buildings surrounded by open ground.

Sensitivity of the AF to other factors, such as location of the subslab and soil-gas sampling point from the building perimeter (**Figures 7h** and **7i**), and the distance and time between indoor air and subsurface vapor samples (**Figures 7j** and **7k**) is relatively minimal implying that the AF is more sensitive to other factors, the sensitivity to such factors is masked by the spatiotemporal variability of the data, or these factors are not critical in VI screening assessments.

Other explanations can likely be put forward to support these findings in addition to those postulated above. Further understanding of key factors affecting the AF might also be possible through a more rigorous multivariate analysis, which is beyond the scope of this paper. Nonetheless, it is hoped that these cursory findings can be used as a starting point to help guide VI data collection and future VI studies.

Summary

A database of over 8,400 paired subsurface and indoor air vapor concentration measurements from various VI sites in California was compiled and analyzed to assess the efficacy of USEPA's default AF = 0.03 for VI screening. The database was extensively filtered to remove lesser quality data and vapor samples potentially affected by background (non-VI) sources. The filtering and analytics invoked in this study are modifications from those applied by USEPA including an emphasis on the AF's reliability to screen indoor air concentrations above risk-based screening levels. The reliability assessment was considered more technically defensible than descriptive statistics and 95th percentiles for calculating AFs given weak correlation of indoor air and subsurface vapor concentration data and uncertainties in key factors affecting the spatiotemporal variability of indoor air data. The reliability assessment resulted in an AF = 0.0008, which was based on an analysis of 643 paired TCE vapor samples. This AF is over an order of magnitude less than the USEPA value (0.03), yet comparable to the 95th percentile of

AFs (0.001) calculated from the same filtered TCE database and the AFs (0.001 – 0.002) previously recommended in California guidance derived using the Johnson and Ettinger (1991) model developed on mass-flux principles.

Descriptive statistics were used to visually correlate AF distributions to various factors commonly believed to directly or indirectly affect the AF. General observations from the analysis suggest that AF assessments based on TCE vapor data are more informative than those based on PCE or chemicals with low vapor source concentrations that are more biased by background (non-VI) sources in indoor air. Parameters with greater influence on the AF are building type, foundation type, sample type, soil type, soil-gas sample depth, HVAC operation and surface cover surrounding the building foundation. Parameters with lesser influence on the AF are related to specifics regarding subsurface sample location (relative to the building perimeter or indoor-air sample location) and timing of subsurface and indoor air vapor sampling.

The value of empirical AF assessments is limited by the inability to account for critical complexities and uncertainties affecting spatiotemporal variability of indoor air and subsurface vapor concentration measurements. In this regard, alternative methodologies focused on mass-flux, longer duration or larger volume concentration measurements, or more detailed characterization at specific buildings may yield more effective VI screening assessments rather than empirical AF methods based on descriptive statistics and 95th percentile values of discrete vapor concentration data. It is hoped that the results of reliability assessment presented in this study can be used to improve VI screening, minimize unnecessary data collection, and focus resources on sites with the greatest risk while other methodologies for VI screening are further developed.

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Disclosure

The authors declare no competing interests.

Key words: vapor intrusion, attenuation factor, vapor intrusion screening, risk-based screening levels

Abbreviations: vapor intrusion (VI), attenuation factor (AF), indoor air vapor concentration (C_{IA}), subsurface vapor concentration (C_{SOURCE}), background indoor air vapor concentration (C_{BGRD}), outdoor air vapor concentration (C_{OA}), indoor air screening level (IASL), subsurface vapor screening level (SSSL), trichloroethylene (TCE), tetrachloroethylene (PCE), quality assurance/quality control (QA/QC)

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Examination of the U.S. EPA's Vapor Intrusion Database Based on Models

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ABSTRACT: In the United States Environmental Protection Agency (U.S. EPA)'s vapor intrusion (VI) database, there appears to be a trend showing an inverse relationship between the indoor air concentration attenuation factor and the subsurface source vapor concentration. This is inconsistent with the physical understanding in current vapor intrusion models. This article explores possible reasons for this apparent discrepancy. Soil vapor transport processes occur independently of the actual building entry process and are consistent with the trends in the database results. A recent EPA technical report provided a list of factors affecting vapor intrusion, and the influence of some of these are explored in the context of the database results.

■ INTRODUCTION

Since the release of U.S. EPA's Office of Solid Waste and Emergency Response (OSWER) draft guidance [1] concerning the vapor intrusion pathway, the U.S. EPA has been collecting site monitoring data to improve its knowledge and understanding of vapor intrusion, and sharing these data and experiences with investigators across the country.[3,4] As of 2012, 2929 paired measurements from 42 vapor intrusion sites across the country have been included in U.S. EPA's Vapor Intrusion database.[2] Of these measurements, "*1,021 (35 percent) are paired groundwater and indoor air measurements, 235 (8 percent) are paired exterior soil gas and indoor air measurements, 1,582 (54 percent) are paired subslab soil gas and indoor air measurements, and 91 (3 percent) are paired crawlspace and indoor air measurements*".[4] The building types represented include "*residential (85 percent), institutional or commercial (10 percent), and multi-use (residential and non-residential) buildings (5 percent)*".[4] Currently, the foci of the database are both chlorinated volatile organic chemicals (VOCs) and volatile petroleum hydrocarbons (PHCs), the latter of which, however, comprise only 3% of the data set.[4] Moreover, other contaminants with vapor intrusion potential, such as mercury or semivolatile organic chemicals (SVOCs) are not included.[4]

Consultants and state regulators have made contribution to the database, and some data were also provided by the EPA's regional offices. Both sampling design information and vapor analytical methods were evaluated to make sure that the sites were correctly characterized and the reported values reliable.[3]

The database consists of a spreadsheet of measured data from vapor intrusion sites. These data have been used to evaluate the importance of various factors governing vapor intrusion. The ratios of indoor air concentration to subsurface source vapor concentration or subslab vapor concentration, termed vapor intrusion attenuation factors, are given particular attention in the database.[3,4] As temporal variability exists for every VI site, a possible solution is to use statistical approaches to analyzing data. For such a huge pool of data in EPA's VI database, the influences of random fluctuations would average out.

In the analyses that accompany this database, most of the focus has been on the indoor air concentration attenuation factors. As is commonly accepted, the attenuation of contaminant concentration in a vapor intrusion pathway occurs during two processes; the first is the transport of the contaminant through the soil and, the second, its entry into the enclosed space of the buildings of concern. These steps are different, and relatively independent of each other in most cases (below). The understanding of these two processes is critical to understanding the data.

Figure 1 shows the measured indoor air concentration (c_{in}) attenuation factor (c_{in}/c_s) as a function of groundwater source vapor concentration (c_s), calculated from Henry's law, based upon measured contaminant concentration in groundwater. All groundwater source vapor concentrations in the EPA database and this article were calculated in this way, but what are shown here are only values taken from the EPA database itself. Figure 1 immediately raises questions regarding the ability of any modeling approach that primarily has a transport focus to capture the trends that are shown. All transport scenarios that do not include biodegradation-type reaction processes should show no trend in attenuation factor with concentration. Leaving out the petroleum data from part a of Figure 1 (which are the data that could potentially be subject to

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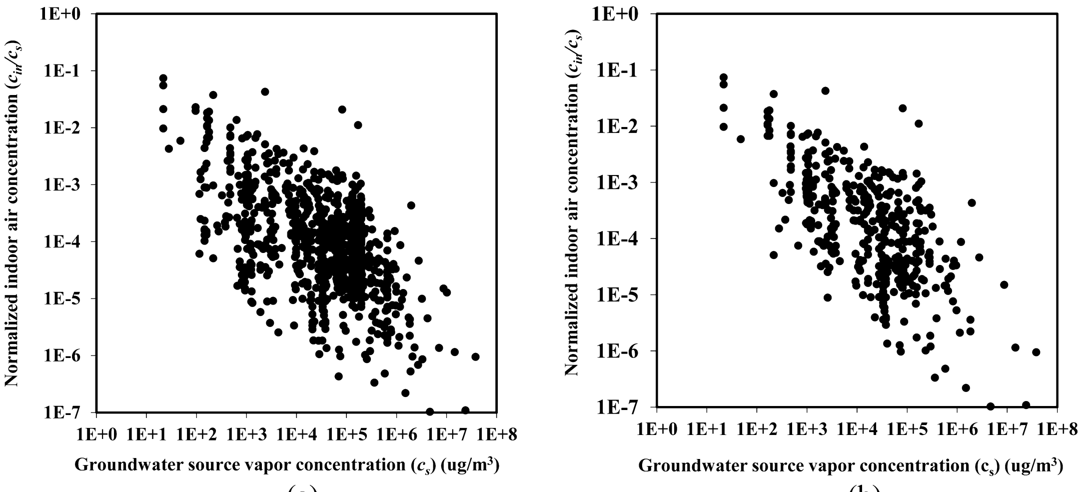
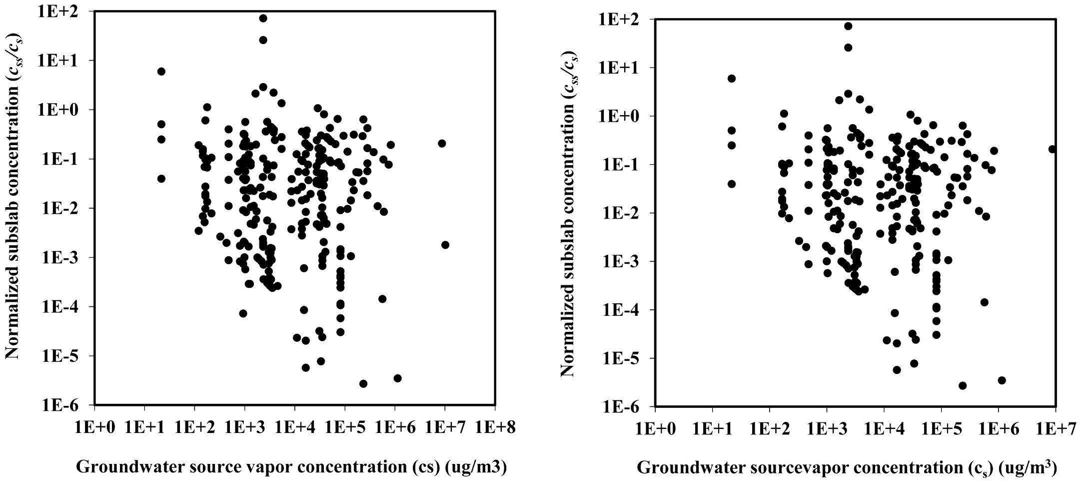


(a) (b)

Figure 1. Calculated groundwater source vapor-to-measured indoor air concentration attenuation factor for (a) all contaminants, (b) tetrachloroethylene (PCE) and trichloroethylene (TCE) data taken from the U.S. EPA's VI database [2].



(a) (b)

Figure 2. Calculated groundwater source vapor-to-measured subslab soil vapor concentration attenuation factor for (a) all contaminants, (b) PCE and TCE in data taken from the U.S. EPA's VI database [2].

biodegradation processes), does not fundamentally alter this picture, as shown in part b of Figure 1. In this study, the chlorinated solvents such as PCE and TCE are considered as nonbiodegradable because, compared to PHCs, they biodegrade much more slowly, often incompletely, and primarily under anaerobic conditions in the subsurface.[4] Published studies show that the mean half-lives of PCE and TCE are years.[5,6]

Thus, there is immediately a question regarding the reliability of any transport-based predictive models of vapor intrusion, as these cannot predict the trends shown in Figure 1. The issue becomes clearer, however, when considering the same data set, but instead plotting the attenuation factor from calculated contaminant source vapor concentration (c_s) to measured contaminant subslab concentration (c_{ss}), as shown in Figure 2. Here, there is still significant data scatter but, more importantly, the trend with concentration is much weaker, if present at all.

The implications of this observation are considered below, in the context of the usual soil vapor transport and building entry models used to describe VI.

EQUATIONS GOVERNING TRANSPORT IN VI SCENARIOS

Soil Vapor Transport. For a groundwater source of contaminant vapor, the soil vapor transport process begins with contaminant being released from that source into the vapor and ends with it arriving at a building foundation.

The general governing equation for soil vapor transport is[7]

$$\phi_{\mathrm{g,w,s}}\frac{\partial c_{\mathrm{ig}}}{\partial t} = -\nabla(q_{\mathrm{g}}c_{\mathrm{ig}}) - \nabla\left(\frac{c_{\mathrm{ig}}}{H_{\mathrm{i}}}q_{\mathrm{w}}\right) + \nabla(D_{\mathrm{i}}\nabla c_{\mathrm{ig}}) - R_{\mathrm{i}} \tag{1}$$

$$\text{Where } \phi_{\mathrm{g,w,s}} = \phi_{\mathrm{g}} + \frac{\phi_{\mathrm{w}}}{H_{\mathrm{i}}} + \frac{k_{\mathrm{oc,i}}f_{\mathrm{oc}}\rho_{\mathrm{b}}}{H_{\mathrm{i}}} \tag{2}$$

In eq 1 $\phi_{\mathrm{g,w,s}}(\partial c_{\mathrm{ig}}/\partial t)$ represents the time dependence of contaminant mass contained in the soil gas, soil moisture, and soil organic carbon as represented in eq 2; $-\nabla(q_{\mathrm{g}}c_{\mathrm{ig}} -\nabla((c_{\mathrm{ig}})/(H_{\mathrm{i}})q_{\mathrm{w}})$ is the convection term reflecting contaminant movement with soil gas and, if relevant, groundwater flow; $\nabla(D_{\mathrm{i}}\nabla c_{\mathrm{ig}})$ describes the diffusion of contaminant in the soil gas phase (contaminant diffusion through the water phase is neglected due to much lower diffusivity in a condensed phase as compared to a vapor phase); q_g is the soil gas flow per unit area [L^3_{gas}/L^2_{soil} /T]; q_w is the groundwater flow per unit area [L^3_{water}/L^2_{soil} /T]; φ_g is the air filled porosity [L^3_{gas}/L^3_{soil}]; φ_w is the moisture filled porosity [L^3_{water}/L^3_{soil}]; H_i is the contaminant Henry's Law constant [$(M_i/L^3_{gas})/(M_i/L^3_{water})$],] linearly relating vapor phase contaminant concentration to water phase concentration; $k_{oc,i}$ is the sorption coefficient of contaminant i to organic carbon in the soil [$(M_i/M_{oc})/(M_i/L^3_{water})$]; f_{oc} is the mass fraction of organic carbon in the soil [M_{oc}/M_{soil}], ρ_b is the soil bulk density [M_{soil}/L^3_{soil}], c_{ig} is the concentration of contaminant i in the gas phase [M_i/L^3_{gas}], D_i is overall effective diffusion coefficient for transport of contaminant i in porous media [L^2/T], R_i is the contaminant i loss rate by biodegradation [M_i/L^3_{soil}/T] and $\varphi_{g,w,s}$ is the effective transport porosity [L^3_{air}/L^3_{soil}], defined in eq 2.

Except possibly for the last term in eq 1, this equation is linear in c_{ig} meaning that it can be rewritten entirely in terms of a nondimensional contaminant vapor concentration. The normally selected reference concentration is that of the contaminant vapor at its source, c_s. The result would be, for example:

$$\phi_{g,w,s}\frac{\partial C^*}{\partial \theta} = -\nabla^* C^* - \nabla^*\left(\frac{C^*}{H_i}\frac{q_w}{q_g}\right) + \nabla^*(D^*\nabla C^*) - r_i \tag{3}$$

Where $\bigtriangledown^*$ represents the nondimensional $\bigtriangledown$ operator, nondimensionalized with respect to some characteristic length scale L, $C^* = (c_{ig}/c_s)$, $\theta = (tq_g/L)$, $D^* = D_iL^3/q_g$, and $r_i = (R_i/c_s)$. The solution for the entire vapor concentration profile in the domain of interest is completely independent of the choice of c_s (i.e., the source vapor concentration), which can even be true for $R_i \neq 0$, if the biodegradation rate is first order in c_{ig}. Of course, eq 3, or the equivalent eq 1, is used in some form in virtually every vapor intrusion model. The value of q_g, which may influence some aspects of the solution of soil gas contaminant profile, normally comes from solution of Darcy's Law for soil gas. This equation does not include any terms that depend on c_{ig} because the contaminant vapor concentration is always much too low to influence overall soil gas concentration or transport. The above results are consistent with the lack of trend in c_{ss}/c_s with concentration in Figure 2, in the sense that the concentration of the source should not affect the normalized subslab concentration at steady state.

Entry into the Building. The attenuation of contaminant soil vapor concentration also occurs during the process of entry into a building. Generally, entry is a result of both diffusion and convection of contaminant through entry cracks or holes, and convection is induced by the indoor air pressurization or depressurization, as appropriate.

The common way to handle this issue is to represent the enclosed space of concern as continuous stirred tank(s) (CST), which are purged by normal building air exchange processes but which receive contaminant through foundation breaches. The two main factors that determine the indoor air attenuation factor are then the total contaminant mass entry rate and separately total building air entry rate, which purges the space of concern.[8] It is the ratio of contaminant entry rate to air entry rate that determines indoor air concentration:

$$c_{in} = \frac{J_s + V_bA_ec_{atm}}{V_bA_e + Q_s} \approx \frac{J_s}{V_bA_e} \tag{4}$$

Where $V_bA_e + Q_s$ is the total air entry rate [L^3/T], $J_s + V_bA_ec_{atm}$ is the total contaminant mass entry rate including any possible atmosphere sources [M/T], c_{in} is the indoor air concentration of the contaminant [M/L^3], J_s is the contaminant mass entry rate from the subsurface alone [M/T], V_b is the volume of the enclosed space [L^3], c_{atm} is the contaminant concentration in atmosphere [M/L^3], A_e is the air exchange rate of the enclosed space [1/T] and Q_s is the volumetric flow rate of soil gas into the enclosed space [L^3/T]

The contaminant mass entry rate can be obtained for entry through a crack, as is assumed in many common VI models[7−13]

$$J_s = \begin{cases} \dfrac{c_{ss}Q_s}{1 - \exp\left(-\frac{Q_sd_{ck}}{A_{ck}D_{ck}}\right)}, & Q_s \neq 0 \\ \dfrac{c_{ss}A_{ck}D_{ck}}{d_{ck}V_bA_e}, & Q_s = 0 \end{cases} \tag{5}$$

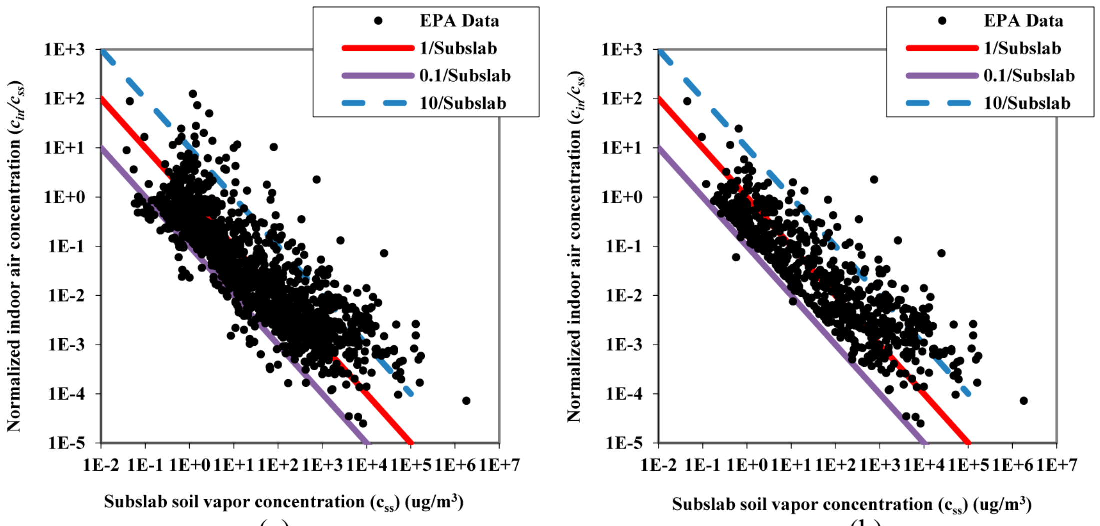
Where A_{ck} is the area of the crack [L^2], c_{ss} is the contaminant subslab crack concentration [M/L^3], $c_{in} \ll c_{ss}$ is assumed, D_{ck} is the contaminant effective diffusivity in the crack [L^2/T], and d_{ck} is the thickness of the crack [L].

Substituting eq 5 into 4

$$\frac{c_{in}}{c_{ss}} \approx \begin{cases} \dfrac{\frac{Q_s}{V_bA_e}}{1 - \exp\left(-\frac{Q_sd_{ck}}{A_{ck}D^{ck}}\right)}, & Q_s \neq 0 \\ \dfrac{A_{ck}D^{ck}}{d_{ck}V_bA_e}, & Q_s = 0 \end{cases} \tag{6}$$

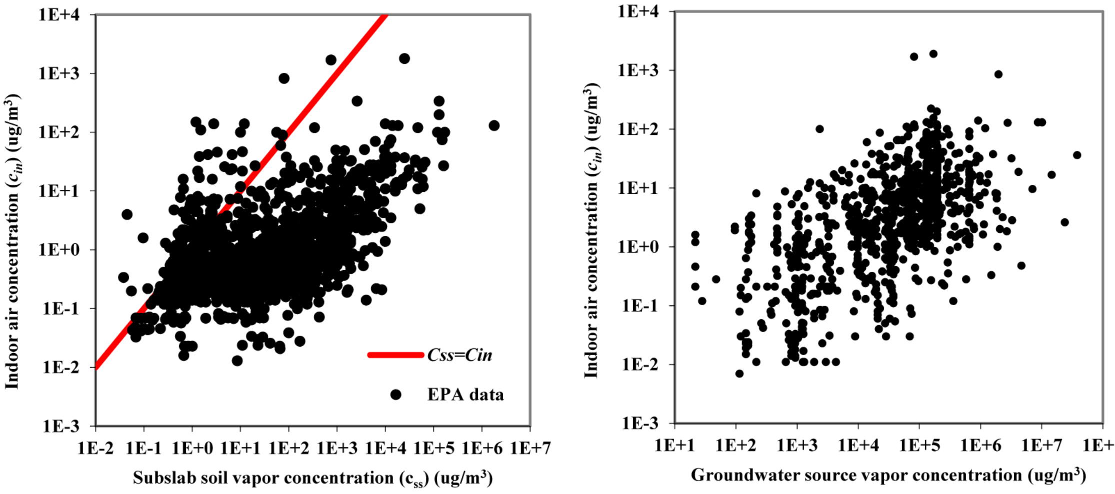
Again, eq 6 shows the indoor air concentration, as normalized by subslab soil vapor concentration, should be independent of the reference (source) concentration, because it has already been established that all normalized soil gas concentration profiles (including subslab) are independent of absolute source concentration; that is, the attenuation factor for indoor air relative to source concentration should thus also be independent of source concentration. This is contrary to Figure 1. Hence, it appears that it is in taking the step from soil gas transport models to the building entry models that the basic structure of current VI models is inconsistent with a concentration dependent trend, such as that shown in Figure 1.

Scenarios involving a permeable wall contaminant entry will be similar to the case for the crack entry scenario in the sense that they will similarly scale linearly with source (and subslab) concentration. Hence, it is not the assumption of crack entry that represents the origin of the problem; any plausible model of entry into the structure should be linear in subslab concentration. Figure 2 has shown that the origin of the strange inverse correlation of indoor air concentration with source concentration does not arise from a peculiarity in soil transport, and the analysis of all plausible entry models likewise cannot offer an explanation of that trend. It remains to look at the factors that actually determine indoor air concentrations, given a certain entry rate of contaminant.



(a) (b)

Figure 3. Measured subslab-to-indoor air concentration attenuation factor for (a) all contaminants (b) PCE and TCE in EPA's VI database.[2]



(a) (b)

Figure 4. Measured indoor air concentration data from the U.S. EPA's VI database;[2] (a) measured indoor air concentration as a function of subslab concentration, (b) measured indoor air concentration as a function of calculated groundwater source vapor concentration.

DISCUSSION

Indoor Air Contaminant Concentration Calculations. Figure 3 presents the measured subslab-to-indoor air concentration attenuation factor as a function of measured subslab soil vapor concentration, from the EPA's VI database results. The trend with concentration is again quite obvious, and once more shows that the measured subslab-to-indoor air concentration attenuation factor is inversely related to measured subslab soil vapor concentration, as expected, given the results of Figure 1 and the conclusion regarding soil transport processes not being source concentration dependent.

The trend in Figure 3 can be explained by considering rough limits on absolute indoor air concentrations, such that the measured levels of c_{in} are actually relatively constant in the range of 0.1 to 10 ug/m^3. It is the act of normalizing the data set of indoor concentrations by measured subslab vapor concentration that leads to an apparent trend with subslab concentration. The measured data on the ordinate of Figure 3 appear mostly to fall in the range of $(0.1[\text{ug/m}^3])/(c_{ss})$ to $(10[\text{ug/m}^3])/(c_{ss})$. This range is substantiated by what is presented in part a of Figure 4, which shows the actual measured indoor air concentration as a function of measured subslab vapor concentration. This figure shows that there is, in fact, no significant trend of indoor air concentration with subslab concentration, perhaps contrary to expectations. In part b of Figure 4, the measured indoor air concentration again ranges over 1−2 orders of magnitude, but here is shown as a function of calculated groundwater source vapor concentration. Because the groundwater source and subslab soil vapor concentration were not measured together for all VI sites included in the EPA VI database, a full comparison of all site data cannot be offered. What part b of Figure 4 shows is that there is only a very weak trend of indoor air concentration with groundwater source concentration. Compared to the wide variation of calculated groundwater source vapor and measured subslab vapor concentrations (7 orders of magnitude), most of the data representing measured indoor air concentration fall in a much narrower range as claimed above. This shows that there must exist processes, which keep the measured indoor air concentration from changing linearly with calculated groundwater source vapor or measured subslab soil vapor concentration.

What can help explain data such as those in Figure 4 are two things. First, typical detection/reporting limits for compounds such as those of interest in Figure 4 are tenths of parts-per-billion-by-volume (PPBv), which corresponds to values of order 0.1 to 1 ug/m^3, depending upon the compound of interest. Thus, it is not surprising to find this as a lower limit to the measured indoor air concentration data; anything lower could not be classified as evidence of vapor intrusion.

The apparent upper limit of 1 to 10 ug/m^3 presently has no obvious explanation. It implies some measure of control of maximum contaminant concentration by other factors. The levels are typically so low that building occupant response to odor threshold is unlikely to be responsible. Instead, there might be factors such as the existence of indoor adsorption equilibria that might come into play. Another possible, but less likely, explanation could be that ambient natural or anthropogenic background concentrations determine the upper limit.[14]

The 2 orders of magnitude scatter in measured indoor concentration data could itself be due the uncertainty or variability of indoor environment, which determines the indoor depressurization and indoor air exchange rates. The uncertainty in these factors makes it unrealistic to hope to calculate more accurately an attenuation factor for the indoor air concentration relative to subslab (or source) contaminant concentration. In 2005, Johnson et al.[15] suggested an empirical air exchange/soil gas entry rate ratio (Q_s/V_bA_e) to replace both the widely used Nazaroff eq (16), which has been used to calculate soil gas entry rate through a perimeter crack (Q_s), and the indoor air exchange rate (A_e). These were previously introduced as independent parameters in the Johnson-Ettinger (J–E) model.[8] In other words, this alternative factor requires establishing a reasonable range of indoor air/subslab contaminant concentration ratio based on data from previous vapor intrusion investigations. This is similar to the idea of dilution factor in models like DF Sweden [17] and DF Norway,[18,19] where an empirical parameter for the ratio of indoor air to source concentration is used. But reference to eq 6 shows that use of this new factor cannot explain data such as those in Figure 1 or 3, because the result still should be independent of calculated groundwater source vapor concentration, when expressed as a nondimensional concentration.

The conclusion is that the EPA VI database, while quite valuable for understanding some aspects of the vapor intrusion process, cannot be looked to for validation of predictions of indoor air contaminant concentrations by VI models. There remain factors, which are not yet fully understood governing the observed indoor air concentrations.

Next, attenuation is turned to a different, but related question. If use is made of VI models that are believed to properly represent all key factors, how well do these do in predicting the values reported in the EPA database?

Environmental Factors and Soil Vapor Transport. The conclusion from most modeling analyses of vapor intrusion is that soil vapor transport processes are relatively independent of the building entry process and therefore the former should normally not be much affected much by human activities or indoor environment.[7,20,21] Soil transport processes can be simulated by using well established methods that are known to depend on certain key factors as may be inferred from eq 1. Site investigation data on in-soil attenuation should be explicable by using measurements of agreed upon specific environmental factors. If transport models are to be judged against field data, this should first be done using data free from biodegradation effects, and free from the inherent unpredictability of indoor processes.

On the basis of Abreu and Johnson' 3D numerical model,[7,10,22] US EPA's OSWER in 2012 published a technical report entitled, "Conceptual model scenarios for the vapor intrusion pathway",[23] in which a summary of factors affecting vapor intrusion were presented in the context of conceptual scenarios (Table 1). Those factors can be classified into three major groups, which are contaminant source, soil conditions, and building conditions. Except for indoor air depressurization and exchange rate, most of them can affect soil vapor transport or at least play a role in establishing the upper boundary conditions (i.e., open ground or building foundation) for this transport.

As shown in Table 1, there are enough factors that may have potential influence on soil vapor transport that it is generally difficult to obtain all necessary input values during routine site investigation. So, the question remains which factors are the most important in particular cases, and this is where modeling work can be of considerable benefit.

Overestimation of Measured Subslab Concentrations in the EPA Database. Figure 5 shows data that speak to the importance of including certain factors into models of vapor intrusion. Yao et al.[20] have shown that for a uniform soil and contaminant vapor source, the full 3D model predictions of perimeter subslab (crack) concentration beneath a structure can be approximated by

$$\frac{c_{ss}}{c_s} = \left(\frac{d_f}{d_s}\right)^{0.7} \qquad (7)$$

where d_f is the foundation (subslab) depth and d_s is the depth of a contaminant groundwater source. This result compared reasonably well with numerous steady-state uniform soil calculations using 3D fluid dynamics models.[7,20]

It is obvious from Figure 5 that the above correlation (and thus the simulations that support it) fails badly at capturing the real data trends in the EPA's VI database. The points shown are all for PCE and TCE, and thus again free from the influence of biodegradation. These are now subslab concentrations, free of the influences of unknown factors discussed above in connection with indoor contaminant concentrations.

The modeling failure illustrated by these results cannot be attributed to a general failure of soil transport models. Consider the dotted line in Figure 5. This is a line of

$$\frac{c_f}{c_s} = \frac{d_f}{d_s} \qquad (8)$$

Here c_f refers to a contaminant concentration at depth d_f in the absence of a building slab. Eq 8 is nothing more than the linear concentration gradient between a vapor source c_s, at a depth d_s, and a ground surface at zero concentration. This must be the situation that exists at steady state, for any uniform soil, and it does not depend on diffusivity or other model details. It is the most basic consequence of diffusion in porous media. This line must define the lowest possible concentration at any depth d_f because any blockage, such as by a foundation slab at the surface, must raise concentrations in the soil below it. Once again, the EPA VI database data fall mainly below this line, which seems to call into question even the most basic aspects of

Table 1. Summary of Factors Affecting Vapor Intrusion[23a]

contaminant source	soil	building
	soil permeability	building foundations (basement, crawl space and slab-on-grade)
source concentration	effective diffusivity	multiple buildings
source depth$^{\mathrm{T}}$	layered soil of different effective diffusivity or permeability (horizontal and vertical)$^{\mathrm{T}}$	indoor pressurization$^{\mathrm{T}}$
source-building separation	biodegradation rate (for petroleum hydrocarbon)	indoor air exchange rate
multiple sources	sorption$^{\mathrm{T}}$	impermeable surface cover
		indoor pressure distribution (wind load)$^{\mathrm{T}}$

[a] The superscript T means the factor takes on special significance in transient cases. Sorption and indoor pressure distribution (wind load) mainly matters in transient cases while factors such as source depth and indoor pressurization matter in both steady and transient cases.

our physical understanding of the soil transport problem in VI modeling. Additionally, recent studies, comparing VI screening tools and site data, also suggested that the VI models tend to overestimate the soil air concentration.[24,25] This necessarily raises the question as to whether the source concentration, c_s, has been correctly characterized. It must seemingly be lower than typically assumed.

Importance of Source Characterization. Normally, an assumption of Henry's law is used to relate measured groundwater source plume concentration to the calculated vapor concentration at this boundary. There are some uncertainties associated with application of this law. In series of studies by Goss and his colleagues, it was shown that partitioning of organic compounds in different phases can be affected significantly by temperature and relative humidity,[26−35] whereas Spencer et al. found that the accumulation of organic chemicals at the soil surface following water evaporation may enhance the volatilization of chemicals with low Henry's law constant.[36] Recent research shows that in a three phase (soil, gas and groundwater) system, the observed partial vapor pressure of toluene can be 1 order of magnitude lower than the predictions by Henry's law.[37]

Though such uncertainties in Henry's law constant might exist, it is difficult to imagine many orders of magnitude error attributable to this source. Thus, the evidence points in the direction of the assumed groundwater source leading to a lower contaminant vapor concentration than calculated from Henry's law.

As already noted, Yao et al.[20] used modeling to show for a scenario with uniform contaminant source and uniform soil diffusivity, that subslab contaminant concentration can be estimated as a simple function of the ratio of foundation depth to source depth using eq 7. This conclusion is not influenced by building operational conditions, and it agrees with the general conclusion that the magnitude of indoor pressurization is always too small to affect soil vapor concentration profile. (Advection can play a role in determining contaminant entry through the building foundation but this is a different part of the process.) Following an earlier analysis by Lowell and Eklund,[38] the Yao et al. analysis has been extended to examining the potential influence of an offset in a lateral (or horizontal) direction between groundwater source and receptor building.[39] The results of this analysis are also shown in part b of Figure 5.

Often, quite limited groundwater monitoring well data have been used to define a contaminant source plume. What has not often been taken into account is the possibility of a lack of vertical uniformity in the plume. If the surface of a contaminated groundwater plume actually consists of relatively clean water, as compared with more contaminated deeper water, then there is an important question of what to use as source concentration. Even if a plume is relatively uniform in cross-section in some locations, it need not be so everywhere. Thus one way of looking at the potential problems associated with plume characterization is shown in part b of Figure 5 based on calculations of soil gas contaminant concentration profiles, including subslab, resulting from a source offset from a building.[39] Here, it is assumed that groundwater exists beneath the site but that the edge of the plume that serves as a real contaminant vapor source is located at a horizontal distance d_h. from the edge of the structure of concern. Part b of Figure 5 illustrates how some displacement of the effective plume edge (shown as r, the ration of horizontal displacement to source

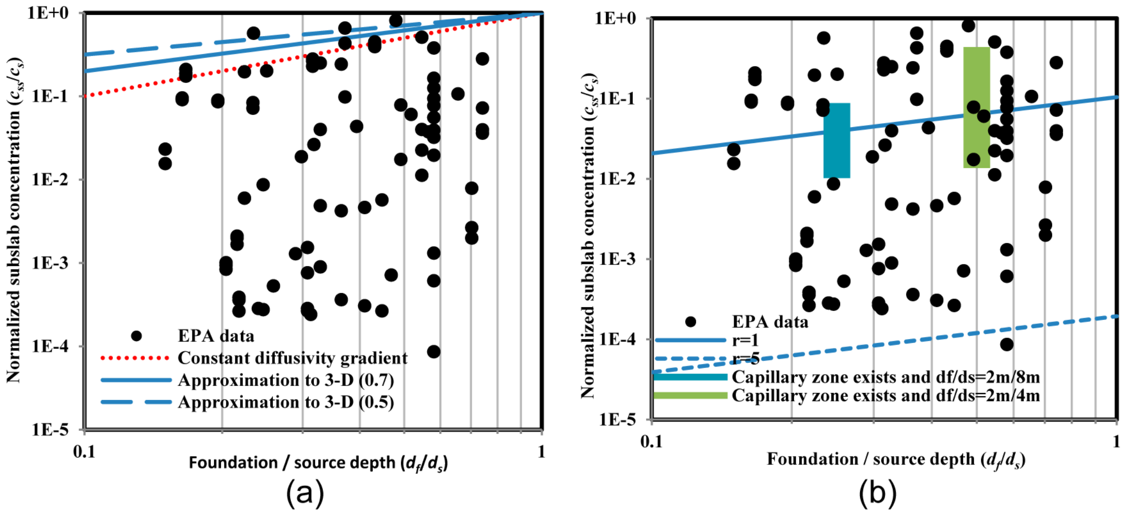


Figure 5. Influence of source characteristics on subslab contaminant concentration predictions subslab concentrations were normalized by vapor concentrations at an assumed groundwater source beneath the building (see Figure 6 for an example of concentration profiles). Actual data points from the U.S. EPA's VI database for PCE and TCE. $r = (d_h/d_s)$ indicates horizontal source-building separation to source depth, and the lines are for otherwise uniform soil. The shaded bands represent calculations for various soil types, in which the influence of capillary zone resistance is taken into account, consistent with realistic soil moisture distribution (source depths of 4 and 8 m assumed for illustration) [21].

depth) can bring the predictions of subslab concentration much more into line with measured values in the EPA VI database. The required values of r are not large.

Another set of comparison results is based on the work of Shen et al.[40] Part b of Figure 5 shows the influence on soil contaminant vapor transport modeling ousing an explicit representation of the capillary zone above the water table. This is a zone of very low diffusivity, and it effectively places a zone of clean water above the groundwater source. Once again, very reasonable representation of an effect of displacing the groundwater source just a bit from where it is typically assumed is seen to have a major effect on prediction of subslab concentration. In one report, it was suggested that only the first 10 cm below groundwater table be used for risk assessment.[41]

It is thus seen as imperative to have a more accurate picture of the groundwater source than has typically been provided by field studies.

Once an estimate of effective source vapor concentration is established, comparison of that value with concentration beneath a large capped area (either nonventilated subslab or underneath a large paved area) should offer some agreement because the capping of the ground surface should lead to a concentration that approaches that of the source, as illustrated in Figure 6. Figure 6 shows the result of a 3D simulation of a steady state VI scenario with uniform soil underlying a structure. It is a simulation for a large structure (or large capping area), which results in the subslab (subcap) concentrations approaching effective source concentration. Obviously, if there is significant advective purging of the subslab/subcap area, this picture would not apply. But in the absence of such purge, the picture is typical. Failure to achieve this level of agreement between the estimate of c_s. and a subslab or subcap concentration suggests that the situation with respect to understanding the source is imperfect, or that transient effects of significance are present.

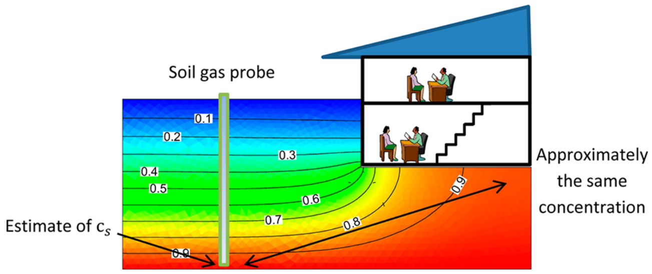


Figure 6. Simulated normalized vapor concentration profile for a typical house with basement scenario.

Thus, there are some important directions suggested by the results of these analyses, which should help advance both VI modeling efforts and field investigations:

(1) Indoor air concentrations can be constrained by both detection limits and some other uncertain factors defining typical maximum concentratio. Hence, subslab-to-indoor air concentration attenuation factors will remain difficult to predict until more is known about the role of such factors.
(2) Apparent groundwater-to-subslab concentrations attenuation is a process that can be influenced by uncertainty in source characterization.
(3) Related to the above, investigation and evaluation of a vapor intrusion site requires careful contaminant characterization of groundwater source plumes. Much apparent attenuation may actually occur in the groundwater itself.

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Notes

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