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EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings

Office of Solid Waste and Emergency Response
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Washington, DC 20460

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Disclaimer

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List of Acronyms and Abbreviations

AF	attenuation factor
CHC	chlorinated hydrocarbon
DCA	dichloroethane
DCE	dichloroethylene
DNAPL	dense (more dense than water) non-aqueous phase liquid
EPA	U.S. Environmental Protection Agency
GW	groundwater
ITRC	Interstate Technology and Regulatory Council
LNAPL	light (less dense than water) non-aqueous phase liquid
MS	Microsoft
OSWER	Office of Solid Waste and Emergency Response
PHC	petroleum hydrocarbon
PCE	tetrachloroethylene (perchloroethylene)
QA/QC	quality assurance/quality control
RL	reporting limit
SVOC	semi-volatile organic compound
TCA	trichloroethane
TCE	trichloroethylene
VI	vapor intrusion
VOC	volatile organic compound
VZ	vadose zone

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1.0 Introduction

1.1 Background

Toxic, volatile substances that are spilled on the ground or released into the subsurface may migrate in the subsurface environment and eventually enter buildings as a gas or vapor by seeping through cracks in basements, foundations, sewer lines and other openings. Vapor flow toward and into a building can be influenced by a number of factors, including atmospheric pressure changes and building depressurization due to operation of exhaust fans or heating units within the building. The flow rate of vapors into a building often is difficult to predict but generally will depend on factors such as subsurface conditions (e.g., soil properties and contaminant characteristics), building design and condition (e.g., cracks and conduits), and differentials in air pressure across the building foundation. Upon entry into a structure, vapors normally mix with the existing air through the natural or mechanical ventilation of the building. Concentrations of indoor vapors may accumulate to a point where the health of occupants (e.g., residents, workers) in those buildings could be at risk.

Vapor intrusion (also referred to as VI) is the general term given to migration of vapors from a contaminant source in the subsurface into indoor air (Johnson and Ettinger, 1991). Vapor intrusion can occur in a wide variety of building configurations (e.g., buildings with basement, crawlspace, or slab-on-grade foundations). Volatile organic compounds (VOCs) are the category of chemicals of greatest potential concern for this pathway, which among other things includes constituents of gasoline (e.g., benzene) and other petroleum fuels, as well as dry cleaning fluids (e.g., tetrachloroethylene [PCE]) and industrial degreasers and solvents (e.g., trichloroethylene [TCE]). Other vapor-forming chemicals of potential interest include certain semi-volatile organic compounds (SVOCs), certain pesticides, and mercury.

The vapor intrusion pathway has become widely recognized as a potentially significant cause of exposure to toxic substances in indoor spaces. Numerous studies have indicated that the air in buildings overlying soil or groundwater contaminated with toxic vapor-forming substances may contain potentially harmful concentrations of these contaminants due to vapor intrusion (see, for example, U.S. Environmental Protection Agency [EPA], 2006, and McDonald and Wertz, 2007).

To help assess and manage human exposures arising from vapor intrusion, EPA issued in November 2002 *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* (EPA, 2002) ("the Draft VI Guidance"). The Draft VI Guidance presents technical and policy recommendations of the Office of Solid Waste and Emergency Response (OSWER) for evaluating subsurface vapor intrusion, based on the understanding of vapor intrusion at that time. OSWER has reviewed the Draft VI Guidance and has concluded that it needs to be updated (EPA, 2010).

The Draft VI Guidance recommended a tiered approach to vapor intrusion assessment. In Tier 2, generic attenuation factor values (which represent the reduction in vapor concentrations between the subsurface source and indoor air) were used to derive screening concentrations for specific subsurface media. These recommended generic vapor attenuation factors were developed from a statistical analysis of the limited number of observations from a few residential sites that OSWER had compiled by that time (see EPA, 2002, Appendix F).

Since the release of the Draft VI Guidance, EPA has been collecting additional observations from vapor intrusion sites to improve its knowledge and understanding of vapor intrusion and, in particular, the attenuation of vapors between the subsurface and indoor air. More specifically, EPA has designed, developed, and managed a database to store and analyze vapor concentration data collected at sites in North America that have been investigated for potential vapor intrusion. A preliminary report about this database was issued, based on data compiled as of 2008 (EPA, 2008), which was subject to external review and public comment.

1.2 Report Content and Purpose

This report provides updated information about EPA's vapor intrusion database (i.e., design, structure, and content) and supersedes the preliminary report on the database (EPA, 2008).

This report presents technical information about sites in the United States that have been investigated for vapor intrusion. The primary focus of the report is the evaluation of concentrations of chlorinated VOCs in and underneath residential buildings based on EPA's vapor intrusion database as of 2010. The database also contains information about petroleum hydrocarbons in and underneath residential buildings, but these data are very limited (comprise less than 3% of the database) and are not discussed further in this document. The technical information provided in this report may be useful for regulators, responsible parties, and others assessing and managing vapor intrusion investigation programs.

1.3 Report Development and Peer Review

This document was developed by EPA's Vapor Intrusion Workgroup (2003–2010) for OSWER, with Dr. Helen Dawson of OSWER's Office of Superfund Remediation and Technology Innovation as the primary investigator and author. This document has undergone extensive internal Agency review, including Regional review and review by other EPA programs, as well as review by members of an expert panel that provided support to OSWER. Additionally, the report has been subjected to EPA's formal external peer-review process. Details of the review process can be found in **Appendix A** of this document.

1.4 Report Organization

The following three sections of this report: describe the development, structure, and contents of the vapor intrusion database (Section 2.0); define vapor attenuation factors and describe key issues to consider when using these vapor intrusion data (Section 3.0); and describe data-screening criteria developed to evaluate the attenuation factors calculated from chlorinated VOC data collected in residential settings (Section 4.0). The report concludes with a discussion of findings (Section 5.0), an overall summary with conclusions (Section 6.0), a list of citations (Section 7.0), and four supporting appendices.

2.0 Database Development

The Draft VI Guidance described and evaluated a vapor intrusion database that OSWER had compiled at that point in time (see EPA, 2002, Appendix F). Shortly after the Draft VI Guidance was released in November 2002, EPA initiated efforts to improve its vapor intrusion database by adding sites and additional site-related information to better represent vapor intrusion in a broader cross-section of the country. In 2003, EPA met with a team of experts and state regulators to lay out the content, design, and quality assurance requirements for the expanded database. Information fields were added to the 2002 database to capture important site information, such as geologic setting, soil characteristics, foundation type, and other building characteristics, as well as more detailed information on the sampling and analysis. The number of fields has been significantly expanded relative to the 2002 database. Starting in 2003, EPA also held a series of national workshops to provide investigators across the country a forum to share data and experiences from a variety of vapor intrusion sites. Vapor intrusion data were gathered from consultants and state regulators, and also through EPA's Regional offices. As a result of these efforts, EPA has significantly expanded its vapor intrusion database, as documented herein.

2.1 Database Structure

EPA's vapor intrusion database is compiled in a Microsoft (MS) Excel spreadsheet to facilitate calculation, evaluation, analysis, and presentation of the attenuation factors in the vapor intrusion database. This spreadsheet was used to perform the analyses described in this report. The user's guide and data dictionary for the spreadsheet are provided in **Appendix B**. The database is available online at the OSWER VI website (http://www.epa.gov/oswer/vaporintrusion/).

As described in subsequent sections of this report, the database primarily contains concentrations of VOCs in and underneath buildings that have been investigated for potential vapor intrusion and accompanying information to support data analyses, documentation, and interpretation.

2.2 Data Entry Criteria

Data generally were compiled only for sites at which VOCs were identified as significant sources of subsurface contamination, and indoor air samples were paired with subsurface samples. Basic data quality parameters were used to determine which data to include in the database. Information reviewed included sampling design information, quality assurance and quality control (QA/QC) information, and the temporal and spatial concurrency of paired vapor samples.

Sampling design information was evaluated to ensure that appropriate methods were used to characterize the site (e.g., groundwater data were obtained from wells screened at or near the water table; soil gas samples were collected when a vapor source was present in the unsaturated zone). Vapor (indoor air and soil gas) analytical methods were also reviewed to determine if the laboratory analyses were conducted according to appropriate EPA Methods (e.g., TO-14, TO-15, TO-17 [EPA, 1999abc]). QA/QC information was reviewed to determine if the analytical data were reliable. Only reliable data obtained with appropriate sampling design and analytical methods were included in the database.

The database comprises VOC concentrations in samples of indoor air, vapors present directly under a building (often called subslab soil gas), soil gas collected exterior to a building at varying depths in the unsaturated zone (often called exterior soil gas), or groundwater samples. The (temporal) concurrency of paired subsurface and indoor air sample concentrations was evaluated as follows: concurrent was taken to mean sample collection within 48 hours for subslab and shallow exterior soil gas data paired with indoor air data, within a few weeks for paired deep exterior soil gas (near the source) and indoor air data, and within a few months for paired groundwater and indoor air data. The longer time frames for the deeper vapor sources were used because these samples tend to exhibit less short-term variation.

Similarly, spatial proximity of the paired data was also considered, and only proximal data were included in the database. For pairings of subslab soil gas and indoor air data, proximal was taken to mean that the samples were collected from the same building. No specific distance criteria were used to define "proximal" exterior soil gas and groundwater data; rather professional judgment was used to determine the allowable separation distance, considering the medium sampled and the geologic, stratigraphic, and hydrogeologic setting in which the samples were taken. Lateral and vertical distances between the building foundation and the sample location generally are recorded in the database for exterior soil gas and groundwater data.

For the majority of the data in the database, sufficient information was available to evaluate the quality of the sample design (e.g., sample locations, depths, source location). For some sites, however, the sampling documentation was limited; these sites were nevertheless included provided appropriate analytical methods were used and the paired samples met the concurrency and proximity criteria.

To ensure accurate data transfer, data entry checks were performed on all the data, and the contributors of the original data were asked to review the data. Information regarding data quality for individual sites is provided in **Appendix C**.

2.3 Database Contents

EPA's vapor intrusion database currently contains indoor air measurements of VOCs paired with groundwater, exterior soil gas, subslab soil gas, or crawlspace measurements for 913 buildings at 41 sites in 15 states (see **Table 1**). EPA Regions 1, 2, 5, 6, 7, 8, 9, and 10 are represented in the database, though the majority of sites in the database are from Regions 1, 2, 8, and 9. A substantial number of the buildings have multiple paired measurements (e.g., several chemicals may be reported for the same sample, multiple sampling events may be reported for the same building, or several types of subsurface samples may be paired with a given indoor air measurement). As a result, the database contains 2,929 paired measurements, of which 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. The building types represented include residential (85 percent), institutional or commercial (10 percent), and multi-use (residential and non-residential) buildings (5 percent). The database contains sample concentrations for chlorinated VOCs and volatile petroleum hydrocarbons (PHCs), although PHCs currently comprise only 3 percent of the data set. The database does not currently include other compounds—such as SVOCs or mercury—that may also produce vapors that can potentially result in detectable indoor air concentrations via the vapor intrusion pathway.

The database also includes, to the extent available, site-specific information such as geologic setting, a general soil type (i.e., fine, coarse, or very coarse),[1] as well as more detailed soil descriptions, vapor source type (e.g., groundwater, soil, and/or non-aqueous phase liquids in the unsaturated zone), building foundation type, and the vertical and horizontal distance between the building and vapor source.

2.4 Data Limitations

EPA's vapor intrusion database represents a range of site conditions (e.g., building uses, soil types, climatic conditions) and types of data (**Table 1**). At some sites, the source of vapors is groundwater, while at other sites the vapor source is contaminated soil. Some sites include information only from residential settings, while others include information only from commercial settings and a few include information from both. At some sites, the indoor air measurements are paired only with groundwater measurements, while at other sites the indoor air measurements are paired only with soil gas measurements. Approximately half of the sites (21 out of 41) have more than one type of paired data.

In some cases, electronic data were available and the entire data set for a site was entered into the database. In other cases, only site reports and maps with plotted concentrations were available, from which a select subset of data, typically from the highest concentration areas, were compiled. Consequently, some sites include all reported measurements for all detected chemicals, which can facilitate evaluation of the vapor intrusion pathway, while other sites include only a partial set of measurements for a single chemical.

The number of buildings sampled at individual sites ranges from one to hundreds of buildings. Of the 41 sites in the database, 31 have fewer than 10 sampled buildings, eight sites have between 10 and 50 sampled buildings, and two sites (Redfield and Endicott) have more than 200 sampled buildings. As a consequence, a relatively high percentage of the total data pairings come from a small group of sites (see **Table 1**), which are located primarily in eastern EPA Regions (1 and 2) and western EPA Regions (8 and 9).

These differences in site conditions and types and amount of data for each site and the uneven distribution of sites among the Regions should be considered when evaluating the analyses and interpretations presented in this report, because they may impart significant bias.

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[1] The general soil type listed generally represents the coarsest soil described in the vadose zone near a sample location, as this soil type offers the least resistance to vapor transport and, therefore, likely serves as the primary migration pathway for vapors. However, if sufficient stratigraphic information was available to indicate finer sediments are laterally continuous, the possibly controlling finer layer's soil type is listed. **Appendix** C provides more detailed information for each site in the database.

Table 1. Summary of information in EPA's vapor intrusion database.

Site Name	City	State	EPA Region	Vapor Source Type	General Soil Type (1)	No. of Bldgs	Building Use(2)		Foundation Type(3)			Media Sampled(4)				Chemicals(5)					
							Residential	Commercial/ Institutional	Basement	Slab on Grade	Crawlspace	Groundwater	Exterior Soil Gas	Subslab Soil Gas	Crawlspace	TCE	PCE	11DCE	111TCA	Other CHCs	PHCs
Alameda Air Station	Alameda	CA	9	LNAPL	Coarse	1		1		1			1	1							●
Aleppo	Mountain View	CA	9	GW	Fine	4	4			4		4	1	3		●					
Alliant*	Littleton	CO	8	GW	Fine	6 (1 in '02)	6		3			9	7			●		●			
Billings PCE	Billings	MT	8	GW	Fine/v. coarse	32	29	3	32			32		32			●				
BP Site	Paulsboro	NJ	2	GW	Coarse	1	1		1			1	1								●
CDOT*	Denver	CO	8	GW	Fine	6	6			6		6				●		●	●	●	
Davis	Troy	MI	5	DNAPL	Coarse	1	1		1			2				●				●	
Denver PCEBB	Denver	CO	8	GW	Fine	7	6	1	7					9		●	●		●	●	●
Eau Claire*	Eau Claire	WI	5	GW	Coarse	3	3		3			6				●				●	
Endicott	Endicott	NY	2	GW	Coarse	232	180	52	145	14		36	36	259		●	●	●	●	●	
Fresh Water Lens	(not available)	MA	1	VZ, GW	Coarse	2		2		2		8	8			●					
Georgetown	Seattle	WA	10	GW	(not available)	2	2		NA	NA	NA		2	2			●		●	●	
Grants	Grants	NM	8	GW	Fine	8	8		2	1	5	8	7		4	●	●			●	
Hamilton-Sundstrand*	Denver	CO	8	GW	Coarse	32 (13 in '02)	32		NA	NA	NA	32						●			
Harcros/Tri State	Wichita	KS	7	GW	Coarse	7	7		4		3	7	6	4			●				

(continued)

Table 1. Summary of information in EPA's vapor intrusion database (continued)

							Building Use$^{(2)}$		Foundation Type$^{(3)}$			Media Sampled$^{(4)}$				Chemicals$^{(5)}$					
Site Name	City	State	EPA Region	Vapor Source Type	General Soil Type $^{(1)}$	No. of Bldgs	Residential	Commercial/ Institutional	Basement	Slab on Grade	Crawlspace	Groundwater	Exterior Soil Gas	Subslab Soil Gas	Crawlspace	TCE	PCE	11DCE	111TCA	Other CHCs	PHCs
Hopewell Precision	Hopewell Junction	NY	2	GW	Coarse	19	19		19			18		25		●			●		
Jackson	Jackson	WY	8	GW	Coarse	2	2			1	1	1	2	1	1		●				
LAFB*	Aurora	CO	8	GW	Coarse	13	13		8	1	4	6		38	47	●	●	●	●	●	
Lakeside Village	Houston	TX	6	VZ, GW	Fine	1		1		1		1				●					
Lockwood	Lockwood	MT	8	GW	Fine	13	13			4	9	11			1	●	●	●		●	
MADEP1*	NA	MA	1	GW	Coarse	2	2		2			2	2			●					
MADEP2*	NA	MA	1	GW	Coarse	1	1		1			1				●					
MADEP3*	NA	MA	1	GW	Coarse	3	3		2	1		2									●
MADEP4*	NA	MA	1	GW	Coarse	1	1		1			2									●
MADEP5*	NA	MA	1	GW	Coarse	1	1		1			1									●
MADEP6*	NA	MA	1	GW	Coarse	2	2		1		1	2									●
MADEP7*	NA	MA	1	GW	Coarse	1	1		1			1									●
Moffett MCH	Mountain View	CA	9	GW	Fine	3	3			3		3				●					
Mount Holly	Mt. Holly	NJ	2	GW	Coarse	1	1		1			1									●
Mountain View*	Mountain View	CA	9	GW	Coarse	5 (7 in '02)	5			5		5	3			●					
Orion Park	Mountain View	CA	9	GW	Fine	8	8			8				9		●	●				
Rapid City	Rapid City	SD	8	GW	Fine	3	3		3			2	1			●					
Raymark	Raymark	CT	2	GW	Coarse	14	14		14					45		●		●	●	●	

(continued)

Table 1. Summary of information in EPA's vapor intrusion database (continued)

Site Name	City	State	EPA Region	Vapor Source Type	General Soil Type $^{(1)}$	No. of Bldgs	Building Use$^{(2)}$		Foundation Type$^{(3)}$			Media Sampled$^{(4)}$				Chemicals$^{(5)}$					
							Residential	Commercial/ Institutional	Basement	Slab on Grade	Crawlspace	Groundwater	Exterior Soil Gas	Subslab Soil Gas	Crawlspace	TCE	PCE	11DCE	111TCA	Other CHCs	PHCs
Redfield*	Denver	CO	8	GW	Fine to Coarse	330 (14 in '02)	330		241	15	73	330						●			
SCM—Cortlandville	Cortlandville	NY	2	GW	V. coarse	40	40		40			40	29	40		●					
Stafford	Stafford	NJ	2	LNAPL	Coarse	3	1	2	1	1	1	3	5	1							●
Twins Inn	Arvada	CO	8	GW	Fine	2	1	1	1	1		2				●	●		●	●	
Uncasville*	Uncasville	CT	1	GW	Coarse	4	4		4			10	8				●		●		
Wall	Wall Township	NJ	2	GW	Coarse	43	43		43			43					●				
West Side Corporation	Brooklyn	NY	2	GW	V. coarse	53	53		53			53	51	52			●				
Wz CA Bay	Mountain View	CA	9	GW	Fine	1		1		1		1				●					

* Site in 2002 database

Abbreviations: DNAPL = dense non-aqueous phase liquid, GW = groundwater, VZ = vadose zone, LNAPL = light non-aqueous phase liquid, TCE = trichloroethylene, PCE = tetrachloroethylene, 11DCE = 1,1,-dichloroethylene, 111TCA = 1,1,1-trichloroethane, CHCs = chlorinated hydrocarbons, PHCs = petroleum hydrocarbons

Notes:

(1) Soil type representing the coarsest soils described in the vadose zone near the sample location unless stratigraphic information is available to indicate finer sediments are laterally continuous.

(2) For each site, the respective entry is the number of buildings in each use category. The database contains indoor air sampling data for each of these buildings.

(3) For each site, the respective entry is the number of buildings in each foundation category.

(4) For each site, the respective entry is the number of pairings in the database of concurrent sampling data from the stated medium with the indoor air sampling data. The number of pairings exceeds the number of buildings at sites when there are multiple chemicals of concern or where paired data were collected at multiple times.

(5) For each site, the symbol "●" designates the VOCs for which paired data are held in the database.

3.0 Vapor Attenuation Factors

The data and analyses presented in this report primarily involve estimating and characterizing empirical vapor attenuation factors, using concurrent, paired data from the updated database. Vapor attenuation refers to the reduction in concentration of volatile substances that occurs during vapor migration in the subsurface (as a result of diffusion, advection, sorption, transformation reactions and other processes in soil), coupled with the dilution that can occur when the vapors enter a building and mix with indoor air (Johnson and Ettinger, 1991). The aggregate effect of these physical and chemical attenuation mechanisms can be quantified through the use of a vapor intrusion attenuation factor (AF_{VI})[2], which is defined as the ratio of the indoor air concentration arising from vapor intrusion (C_{IA-VI}) to the subsurface vapor concentration (C_{SV}) at a point or depth of interest in the vapor migration pathway:

$$AF_{VI} = \frac{C_{IA-VI}}{C_{SV}} \qquad \text{Equation 1}$$

As defined, AF_{VI} is an inverse measurement of the overall dilution that occurs as vapors migrate from a subsurface source into a building; AF_{VI} values decrease with increasing dilution. Johnson and Ettinger (1991) utilized the symbol α for the vapor intrusion attenuation factor. The symbols α and *AF* are used interchangeably in the literature to denote the vapor intrusion attenuation factor.

For purposes of calculating AF_{VI}, subsurface vapor concentrations (C_{SV}) may be measured directly under a building (often called subslab soil gas or just subslab), measured exterior to a building at varying depths in the unsaturated zone (often called exterior soil gas), or derived from groundwater concentrations by converting the dissolved concentration to a vapor concentration assuming equilibrium conditions (i.e., by multiplying the groundwater concentration by the chemical's dimensionless Henry's law constant[3] at the groundwater temperature *in situ*) (EPA, 2001). Subfloor vapor concentrations may also be measured in building crawlspaces. Although crawlspace samples are not strictly subsurface samples, they represent the vapor concentration underlying a building's living space. Thus, crawlspace samples may be evaluated in a manner similar to subsurface vapor samples.

The overall vapor intrusion attenuation factor (AF_{VI}) can be interpreted as the product of two vapor attenuation components, as follows:

$$AF_{VI} = \frac{C_{IA-VI}}{C_{SS}} \times \frac{C_{SS}}{C_{SV}} \qquad \text{Equation 2a}$$

$$AF_{VI} = AF_{bldg} \times AF_{soil} \qquad \text{Equation 2b}$$

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[2] *AF* is used in this report to represent attenuation factors to reinforce the distinction between an empirical attenuation factor, which potentially reflects contributions to indoor air from background sources, and the true (or intrinsic, theoretical) vapor attenuation factor for a given building, which does not. Johnson and Ettinger (1991) used the symbol α for the true vapor intrusion attenuation factor (designated herein as AF_{VI}). Figures 7a and 7b further illustrate this distinction.

[3] The equations and chemical properties used to convert groundwater concentrations to vapor concentrations at groundwater temperatures *in situ* are provided in **Appendix D**.

where the building attenuation factor (AF_{bldg}) expresses the ratio of the indoor air concentration arising from vapor intrusion ($C_{IA\text{-}VI}$) to the subslab (or subfloor) soil gas concentration underneath the specific building (C_{SS}), and the soil attenuation factor (AF_{soil}) expresses the ratio of the subslab soil gas concentration (C_{SS}) to the vapor concentration at a point or depth of interest in the vapor migration pathway (C_{SV}) (i.e., the attenuation that occurs in the vadose zone). The value of AF_{soil} will depend on site-specific factors that influence vapor migration in the subsurface (e.g., soil type[s] and layering; migration distance; transformation reactions, if any). The value of AF_{bldg} will depend on site-specific factors that influence vapor intrusion into and mixing within the respective building (e.g., construction and integrity of the building foundation; pressure differences between the subsurface and the building interior; indoor air exchange rate; interior ventilation and air flow; size, geometry, and compartmentalization of the building).

3.1 Factors Influencing Empirical Vapor Attenuation Estimations

Algebraically and at the conceptual level presented above, the definition and calculation of the vapor attenuation factor are simple. It can be challenging, however, to develop a value of the vapor attenuation factor that is representative of the long-term average (i.e., chronic) exposure condition experienced by occupants in a specific building, which is generally of interest in vapor intrusion assessments. Major complicating factors include:

- spatial and temporal variability in the subsurface vapor and indoor air concentrations, which will manifest in variability in the attenuation factors calculated for a building or set of buildings, and
- the contributions of background sources to indoor air concentrations, which may impart a high bias to the attenuation factors calculated for a building or set of buildings.

The following sections identify several of the primary contributors that can impart variability or bias to empirical vapor attenuation factors and discuss how they influenced the presentation, evaluation, and interpretation of attenuation factors derived from the database.

3.2 Spatial and Temporal Variability

As described earlier, vapor intrusion attenuation factors are expressed as the ratio of the concentration of a chemical of interest in indoor air to its concentration in subsurface vapor. Any spatial or temporal variability in indoor air and subsurface vapor concentrations will contribute to the variability in the empirically derived attenuation factors. This section uses information in the database to illustrate the level of variability that may be observed in vapor concentrations and, consequently, empirical attenuation factors.

Buildings vary significantly in their susceptibility to vapor intrusion, even in areas with widespread and significant subsurface contamination. As a result, vapor intrusion is highly building specific because of differences in building construction, foundation type, physical condition of the foundation, air exchange rate, building operation, and other building characteristics. Thus, indoor air concentrations can vary considerably from building to building, even when depth to the source and subsurface source concentrations are similar. This spatial variability among buildings' characteristics will contribute to the variability in the attenuation factors calculated for a set of buildings at a site. Volatile chemical concentrations in indoor air can also vary over time in a given building because of seasonal differences in ventilation, building operation (e.g., heating and cooling), temporal differences in the subslab soil gas concentrations underneath the building, and meteorological conditions, among other factors. This temporal variability in indoor air concentrations will manifest in variability in the attenuation factors calculated for a building.

For example, **Figure 1** shows that TCE concentrations in indoor air vary by approximately two orders of magnitude among six residential buildings within a small, two-block area at the Lowry Air Force Base with similar groundwater concentration and depth to groundwater. (The type of foundation—and, therefore, the building level sampled—varies among these six buildings, which commonly occurs at vapor intrusion sites.) **Figure 1** also shows that indoor air samples collected (every 2 months for a year) in the same six residences may vary by one to two orders of magnitude. This spatial and temporal variability in indoor air concentrations manifests in significant variability in the attenuation factors calculated for the six buildings of this example, as shown in **Figure 2**. The attenuation factors for individual buildings range over one order of magnitude and vary one to two orders of magnitude among buildings. As a consequence, the combined attenuation factors for these six buildings, which are co-located within a small area, range over three orders of magnitude. Volatile chemical concentrations in indoor air at different locations within individual buildings can also vary over time because of incomplete mixing within the building, spatial differences in the subslab soil gas concentrations underneath the building, and differences in the number and type of entry points in the foundation through which vapor may migrate, among other factors. In general, indoor air concentrations tend to exhibit less variability across space (at the same floor level) but more variability across time (Folkes et al., 2009). These generalizations are highly dependent on the individual building's construction, condition, and operation (e.g., ventilation), as well as numerous atmospheric and climatic factors, which can influence the rate of entry (intrusion) of soil gases into the building's indoor air.

Soil gas concentrations measured exterior to buildings also may not be spatially uniform, depending on the location and geometry of the vapor source relative to the building, among other factors. As a result, exterior soil gas concentrations can exhibit substantial spatial variability. For example, exterior soil gas concentrations concurrently sampled on all four sides of six residential buildings at the Grants, NM, site vary by up to two orders of magnitude around the buildings sampled (**Figure 3**). This spatial variability may be attributed to factors such as vertical and horizontal heterogeneity in soil types and soil properties (such as moisture content). Soil gas concentrations also may vary temporally, depending on meteorological and hydrogeological processes, among other factors. In addition, sample collection issues may influence exterior soil gas concentrations (ITRC [Interstate Technology and Regulatory Council], 2007, Appendix D).

Subslab soil gas concentrations (measured directly underneath building foundations) also may be spatially and temporally variable, depending on the location and geometry of the vapor source relative to the building, meteorological conditions and building conditions, among other factors. For example, data from the Raymark site show that subslab soil gas concentrations collected contemporaneously from multiple locations within an individual building may vary up to an order of magnitude (**Figure 4**). Subslab soil gas data for the Lowry Air Force Base show that subslab soil gas samples collected contemporaneously from individual homes in a one- or two-block area over a plume may differ by more than one order of magnitude and vary at individual locations by more than one order of magnitude over a year (**Figure 5**).

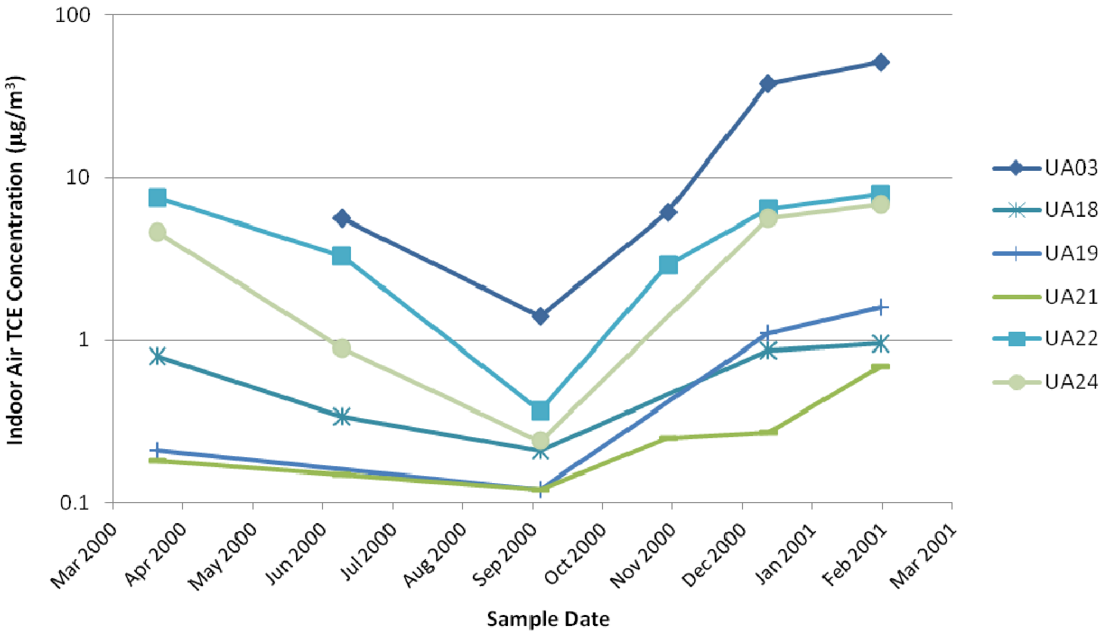

Figure 1. **Spatial and temporal variability of TCE in indoor air at six residential buildings at the Lowry Air Force Base, Colorado, with similar groundwater concentration and depth to water.**

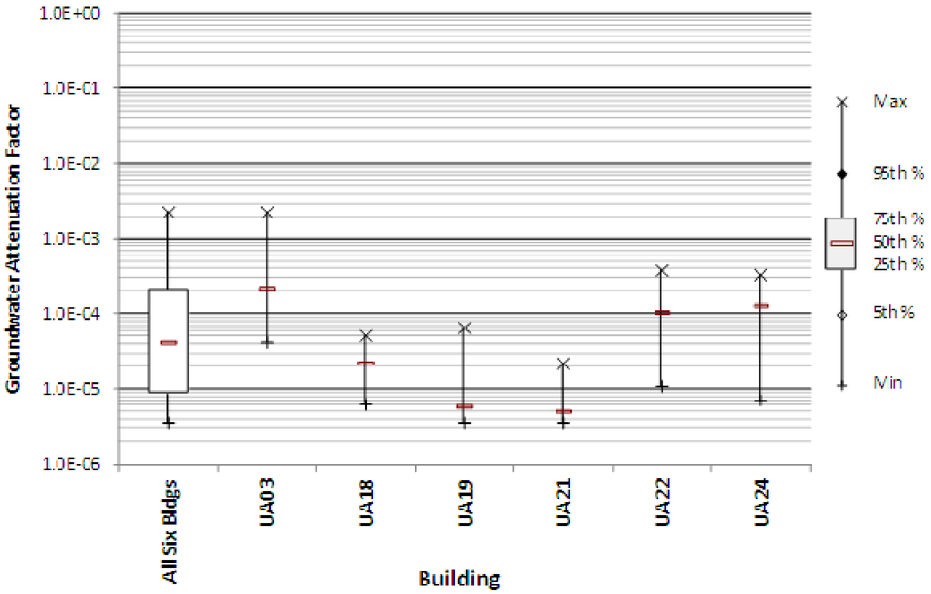

Figure 2. **Variability in TCE groundwater-to-indoor air attenuation factors for six residential buildings at the Lowry Air Force Base, Colorado.**

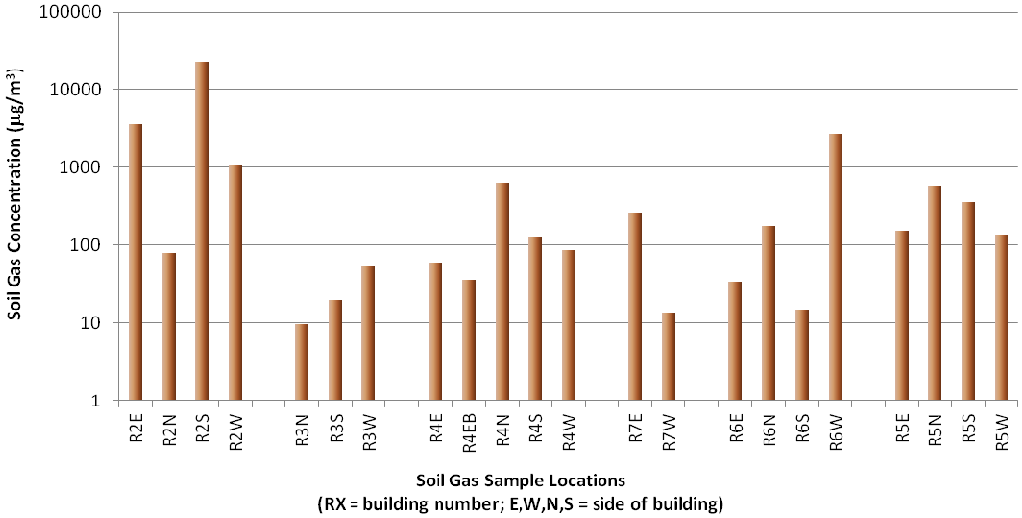

Figure 3. Spatial variability of TCE in exterior soil gas adjacent to six residential buildings in Grants, New Mexico.

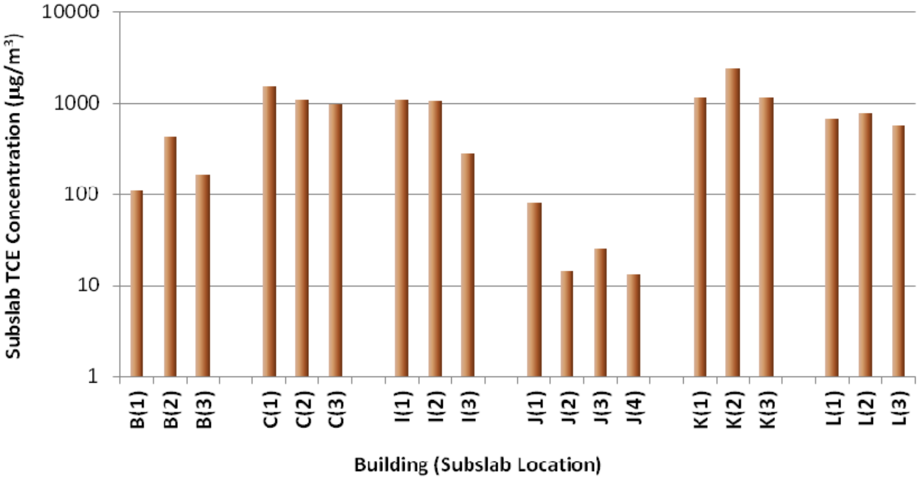

Figure 4. Spatial variability of TCE in subslab soil gas within six residential buildings at the Raymark Superfund site, Connecticut.

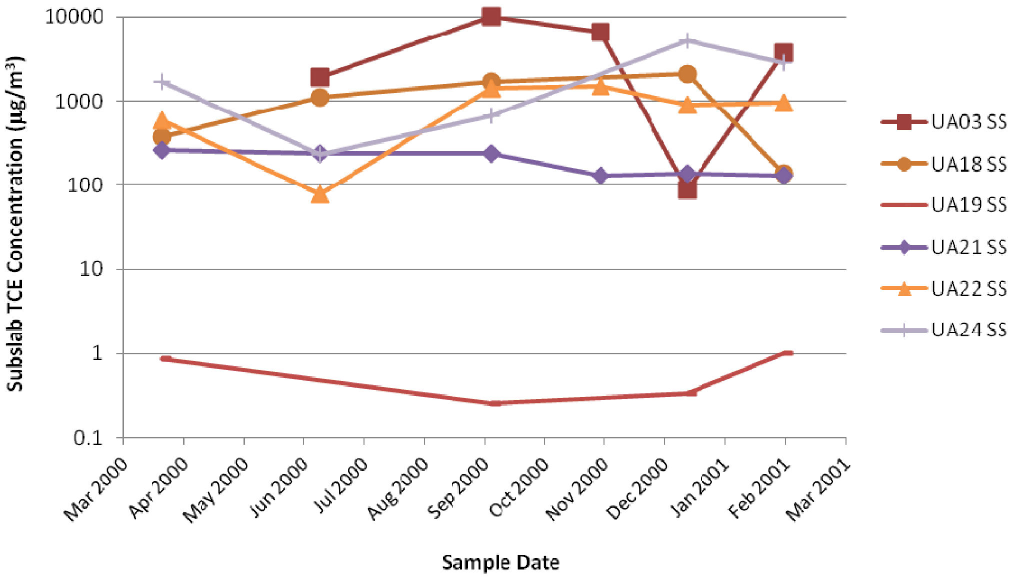

Figure 5. Spatial and temporal variability of TCE in subslab soil gas at six residential buildings at the Lowry Air Force Base, Colorado.

There also may be significant differences between subslab soil gas concentrations underlying a building and soil gas concentrations measured exterior to the building. For example, there are six sites with a total of 98 buildings in EPA's vapor intrusion database for which concentrations were measured in both subslab soil gas (beneath the building foundation) and exterior soil gas samples (**Figure 6**). Four of the six sites and about a third of the buildings (27 buildings), subslab soil gas concentrations exceed the measured exterior soil gas concentrations. In other words, the exterior soil gas concentrations were lower than the concentration directly under the building for approximately a third of the buildings at which both subslab soil gas and exterior soil gas samples were collected. Differentiating the data by horizontal distance and depth to the exterior soil gas sample (**Figure 6**) shows that soil gas samples collected at depths greater than 3 meters (called deep in the figure; see orange circles and red squares) tend to provide better results (exterior soil gas concentrations greater than subslab soil gas concentrations). These data suggest that exterior soil gas concentrations collected at depths shallower than 3 meters may not be representative of soil gas concentrations measured directly beneath the building foundation.

Groundwater concentrations typically are not measured directly below buildings. In some cases, interpolated values are used; in other cases, the value of the nearest sample is used. The result is the possible introduction of high or low bias in concentration when a nearby or interpolated value does not accurately represent conditions under the respective building. Interpolation of groundwater concentrations underlying buildings is particularly difficult when steep concentration gradients are present. Additional variability may be introduced by different groundwater well-screen lengths and sampling depths and by temporal variability in groundwater concentrations.

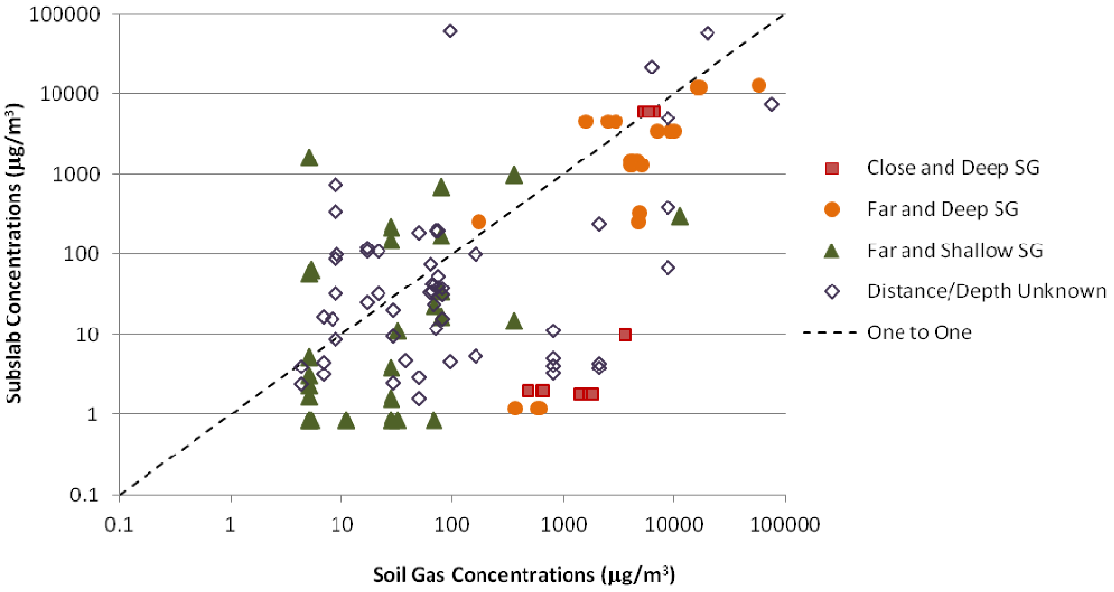

Figure 6. Exterior soil gas versus subslab soil gas concentrations for buildings with both types of data in EPA's vapor intrusion database differentiated qualitatively by horizontal distance to building and depth to the exterior soil gas sample.

In summary, many factors can influence the observed concentrations in environmental media. Factors such as heterogeneous geologic conditions, sample design and collection issues, and seasonal effects can lead to significant spatial and temporal variability in subsurface concentrations. Factors such as variable building conditions and occupant habits can lead to significant spatial and temporal variability in concentrations in indoor air. These factors may impart bias when calculating concentration ratios, depending on the extent to which the samples accurately represent the spatial and temporal variability of the indoor air concentrations and the subsurface vapor concentrations affecting the building. Because the factors influencing subsurface vapor and indoor air variability are largely independent, ratios of the indoor air and surface vapor concentrations (i.e., the calculated empirical attenuation factors) will likely exhibit even greater variability.

The spatial and temporal variability in observed subsurface and indoor air concentrations within and among buildings mean that for every site, and every structure in an area of similar subsurface contamination, a range of empirical attenuation factors would likely be calculated from a series of discrete indoor air and subsurface vapor concentrations measured at different points in space or at different times. Considering this variability, a statistical approach to characterizing the empirical attenuation factors was adopted in the 2002 Draft VI Guidance and a similar approach is used in this report, as described in Section 4.0 and documented in Section 5.0.

3.3 Background Indoor Air Concentrations

Many volatile chemicals that could present a potential vapor intrusion issue at contaminated sites can also be found indoors due to sources unrelated to subsurface contamination (EPA, 2011a). These sources may include emissions from consumer products, home furnishings, building materials, combustion sources, and outdoor sources. Contributions of volatile chemicals from sources other than vapor intrusion are often called "background" sources. Thus, to determine the extent to which vapor intrusion impacts indoor air concentrations, it is appropriate to consider the contributions of background sources to indoor air concentrations.

The influence of background indoor air concentrations ($C_{IA\text{-}BKGD}$) on empirical attenuation factors (AF_{EMP}) can be anticipated by modifying Equation 1, as follows:

$$AF_{EMP} = \frac{C_{IA}}{C_{SV}} = \frac{(C_{IA-VI} + C_{IA-BKGD})}{C_{SV}} = AF_{VI} + \frac{C_{IA-BKGD}}{C_{SV}} \qquad \text{Equation 3}$$

When background sources contribute to indoor air concentrations, the empirical attenuation factor (AF_{EMP}) will be biased high relative to the true vapor intrusion attenuation factor (AF_{VI}) (i.e., toward higher, more conservative values and, therefore, less apparent dilution). The bias varies in proportion to the relative contribution of background sources ($C_{IA\text{-}BKGD}$) to the total indoor air concentration (C_{IA}).

As shown previously, the true vapor intrusion attenuation factor (AF_{VI}) is a combination of the attenuation that occurs in soil (AF_{soil}) and the attenuation that occurs in the building (AF_{bldg}). Whereas the soil attenuation factor is generally not expected to be significantly influenced by background sources, the empirical building attenuation factor ($AF_{EMP,bldg}$) may be biased high, depending on the relative contribution of background sources to the total indoor air concentration. This can be shown by combining Equations 3, 2a, and 2b, as follows:

$$AF_{EMP} = \frac{C_{IA}}{C_{SV}} = \frac{(C_{IA-VI} + C_{IA-BKGD})}{C_{SV}} = \frac{(C_{IA-VI} + C_{IA-BKGD})}{C_{SS}} \times \frac{C_{SS}}{C_{SV}} \qquad \text{Equation 4a}$$

$$AF_{EMP} = [\, AF_{bldg} + \frac{C_{IA-BKGD}}{C_{SS}} \,] \times AF_{soil} \qquad \text{Equation 4b}$$

This analysis shows that the empirical attenuation factor (AF_{EMP}) is likely to approximate "true" attenuation due to vapor intrusion (AF_{VI}) when the subsurface concentration (C_{SV}), and particularly the subslab soil gas concentration (C_{SS}), is substantially greater than the background indoor air concentration ($C_{IA\text{-}BKGD}$). The empirical building attenuation factor ($AF_{EMP,bldg}$) is represented by [AF_{bldg} + ($C_{IA\text{-}BKGD}/C_{SS}$)] in Equation 4b.

The EPA document Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences: A Compilation of Statistics and Implications for Vapor Intrusion (EPA, 2011a) (hereafter referred to as the Background Indoor Air Document) provides descriptive statistics for background indoor air concentrations obtained from a recent compilation of indoor air quality studies in North American residences. A summary of this information is reproduced in **Table 2**, which is derived from indoor air quality studies where samples were collected starting in 1990 and later, because background concentrations for many VOCs measured after that time were judged to be more representative of current background levels than earlier measurements.

Table 2. **Summary statistics[4] for background indoor air concentrations of common VOCs measured in North American residences between 1990 and 2005 (all concentrations expressed in µg/m^3) (EPA, 2011a).**

Compound	Number		Range Percent Detect	Total percent Detects	RL Range	Range of 50th Percent	N*	Range of 75th Percent	N	Range of 90th Percent	N	Range of 95th Percent	N
	Studies	Samples											
Benzene	14	2,615	31–100	91.1	0.05–1.6	<RL–4.7	14	1.9–7.0	9	5.2–15	11	9.9–29	5
Carbon tetrachloride	6	1248	1–100	53.5	0.15–1.3	<RL–0.68	6	<RL–0.72	3	<RL–0.94	5	<RL–1.1	2
Chloroform	11	2,278	9–100	68.5	0.02–2.4	<RL–2.4	11	<RL–3.4	7	<RL–6.2	9	4.1–7.5	5
Dichloroethane, 1,1-	2	682	1	1	0.08–0.25	<RL	2	<RL	2	<RL	2	<RL	2
Dichloroethane, 1,2-	7	1,432	1-25	13.8	0.08–2.0	<RL	7	<RL–0.08	6	<RL–0.4	7	<RL–0.2	4
Dichloroethylene, 1,1-	2	475	7-45	13	0.01–0.25	<RL	2	<RL-0.37	2	<RL-0.8	2	0.7	1
Dichloroethylene, cis 1,2-	3	875	1–9	4.9	0.25–2.0	<RL	3	<RL	3	<RL	3	<RL–1.2	3
Ethylbenzene	10	1,484	26–100	85.7	0.01–2.2	1–3.7	10	2–5.6	5	4.8–13	7	12–17	3
Methyl tert-butyl ether (MTBE)	4	502	9–70	54.5	0.05–1.8	0.025–3.5	4	0.03–11	4	0.03–41	4	71–72	2
Methylene chloride	8	1,724	29–100	79.1	0.12–3.5	0.68–61	8	1.0–8.2	6	2.0–510	8	2.9–45	4
Tetrachloroethylene	13	2,312	5–100	62.5	0.03–3.4	<RL–2.2	13	<RL–4.1	8	<RL–7	10	4.1–9.5	5
Toluene	12	2,065	86–100	96.4	0.03–1.9	4.8–24	12	12–41	7	25–77	9	79–144	4
Trichloro-1,2,2-trifluoroethane, 1,1,2- (Freon 113)	3	600	1–56	37.5	0.25–3.8	<RL–0.5	3	<RL–1.1	3	<RL–1.8	3	<RL–3.4	2
Trichloroethane, 1,1,1-	9	1,877	4–100	53.4	0.12–2.7	<RL–5.9	9	<RL–7	7	<RL–68	8	3.4–28	5
Trichloroethylene	14	2503	1–100	42.6	0.02–2.7	<RL–1.1	14	<RL–1.2	9	<RL–2.1	11	0.56–3.3	5
Vinyl chloride	4	1484	0–25	9.2	0.01–0.25	<RL	4	<RL	4	<RL–0.04	4	<RL–0.09	4
Xylene, m/p-	10	1,920	52–100	92.9	0.4–2.2	1.5–14	10	4.6–21	7	12–56	9	21–63.5	4
Xylene, o-	12	2,004	31–100	89.0	0.11–2.2	1.1–3.6	12	2.4–6.2	7	5.5–16	9	13–20	4

* N = Number of studies reporting the percentile.

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[4] All summary statistics reported by an individual study for an individual chemical were included in this compilation, with the following exceptions: if all statistics, including the maximum reported value, for a chemical were below an individual study's reporting limit for that chemical, the statistics for that chemical in that study were not included in this compilation.

Table 3 presents summary statistics for indoor air concentrations measured in residential settings at vapor intrusion sites in EPA's vapor intrusion database. Comparing the chemical-specific results shown in **Tables 2** and **3** reveals that for a number of these chemicals—including 1,1-dichloroethane; 1,1,1-trichloroethane; 1,1,2-trichloro-1,2,2-trifluoroethane and the PHCs (e.g., benzene, toluene, ethylbenzene, and xylenes)—the range of indoor air concentrations at the vapor intrusion sites in the database is roughly equivalent (at least through the 75th percentile) to the range of the background indoor air concentrations, as presented in the Background Indoor Air Document. If the concentrations in the Background Indoor Air Document are representative of "background" levels during site-specific vapor intrusion investigations, empirical attenuation factors for these chemicals are likely to be biased high (indicating less attenuation than is actually occurring). Comparing the chemical-specific results shown in **Tables 2** and **3** reveals that for other chemicals—such as 1,1-dichloroethylene; cis-1,2-dichloroethylene; tetrachloroethylene; and trichloroethylene—a substantial proportion (25 percent or more) of the indoor air concentrations at the vapor intrusion sites in EPA's database tends to be higher than background levels, as presented in the Background Indoor Air Document. Empirical vapor attenuation factors for these chemicals are expected to generally yield estimates relatively unbiased by background sources.

The influence of background sources on the empirical attenuation factor is illustrated in **Figures 7a** and **7b** for a hypothetical case where the "true" building attenuation factor (AF_{bldg}) is 0.001 and the background indoor air concentration ($C_{IA\text{-}BKGD}$) is 1 µg/m^3. Hypothetical observed indoor air concentrations (**Figure 7a**) and the corresponding hypothetical empirical attenuation factors (**Figure 7b**) are plotted for a broad range of subslab soil gas concentrations (C_{SS}) spanning six orders of magnitude (shown on the x-axis). When no background sources are present ($C_{IA\text{-}BKGD} = 0$), one expects a linear relationship between indoor air concentration and the subslab soil gas concentrations and, therefore, a constant-valued attenuation factor. On the other hand, when background sources are present, a linear relationship between the observed indoor air concentration and subslab soil gas concentrations (the positive-sloped portion of the line in **Figure 7a**) is observed only when indoor air concentrations are greater than the background concentration ($C_{IA\text{-}BKGD} = 1$ µg/m^3 in this hypothetical case). A constant-valued attenuation factor (the horizontal portion of the line in **Figure 7b**) is observed only at high subslab soil gas concentrations (above subslab soil gas concentrations of about 10,000 µg/m^3 in this hypothetical case). At smaller subslab soil gas concentrations (less than about 100 µg/m^3 in this hypothetical case), the background contribution to indoor air concentrations becomes larger than the subsurface contribution, which manifests as a plateau in indoor air concentrations (horizontal portion of the line at 1 µg/m^3 in **Figure 7a**) and imposes an upward bias in the empirical attenuation factor (negative-sloped portion of the line in **Figure 7b,** below subslab soil gas concentrations of about 1,000 µg/m^3 in this hypothetical case). Intermediate subslab soil gas concentrations (between 100 µg/m^3 and 10,000 µg/m^3 in this hypothetical case) represent a transition between these two limiting cases.

Table 3. Indoor air concentrations in residences at sites included in EPA's vapor intrusion database.

Compound	Summary of EPA Database of Residential Indoor Air Concentrations				Indoor Air Concentrations (µg/m^3) at Selected Percentiles				
	Number of Sites	Number of Samples	Percent Detect	Range of Reporting Limits (µg/m^3)	25th Percentile	50th Percentile	75th Percentile	95th Percentile	Maximum
Benzene	7	14	100	0.3	1.2	2.0	6.8	19	26
Carbon tetrachloride	1	1	100	Unknown	—	—	—	—	1
Chloroform	2	4	100	0.2	—	1.3	—	—	1.4
Dichloroethane,1,1-	5	50	64	0.01–0.16	0.02	0.05	0.22	0.88	17
Dichloroethylene, 1,1-	8	466	92	0.01–0.11	1.4	4.2	14	49	131
Dichloroethylene, cis 1,2-	7	105	74	0.01–0.97	0.03	0.22	1.1	6.3	31
Dichloroethylene, trans 1,2-	2	7	71	<0.1 – 0.7	—	0.12	—	—	8.7
Ethylbenzene	7	9	100	0.1	1.9	3.0	5.4	15	15
Methyl tert-butyl ether (MTBE)	1	1	100	Unknown	—	—	—	—	1.8
Tetrachloroethylene	13	378	87	0.018–2.7	0.55	1.5	5.3	44	1,896
Toluene	9	15	100	0.1	5.9	12	35	63	87
Trichloro-1,2,2-trifluoroethane, 1,1,2-	1	124	95	0.22–2.6	0.49	0.63	0.70	0.88	4.3
Trichloroethane, 1,1,1-	7	245	95	0.17–1.8	0.32	1.0	2.4	20	140
Trichloroethylene	20	435	77	0.011–1.8	0.14	0.8	4.5	32	850
Vinyl chloride	4	19	47	0.04–0.55	0.03	0.03	0.07	1.0	1.1
Xylenes	8	15	100	0.1–0.3	2.1	7.5	16	41	100

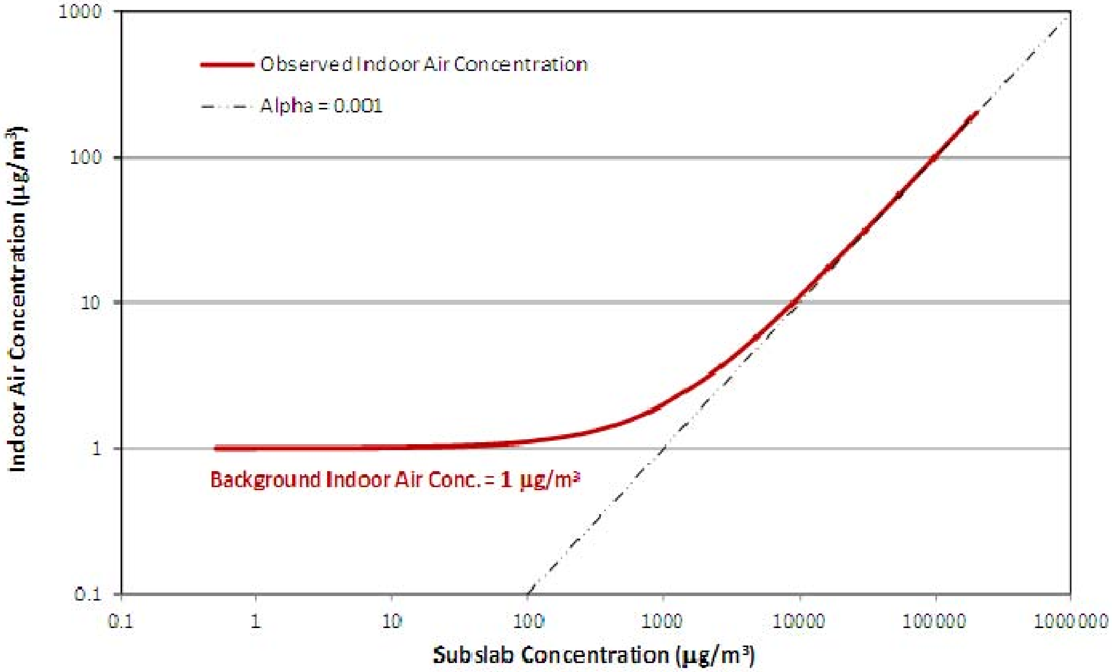

Figure 7a. Hypothetical case illustrating the influence of background sources on observed indoor air concentrations.

The hypothetical background indoor air concentration is 1 µg/m^3 and the hypothetical "true" vapor intrusion building attenuation factor is 0.001.

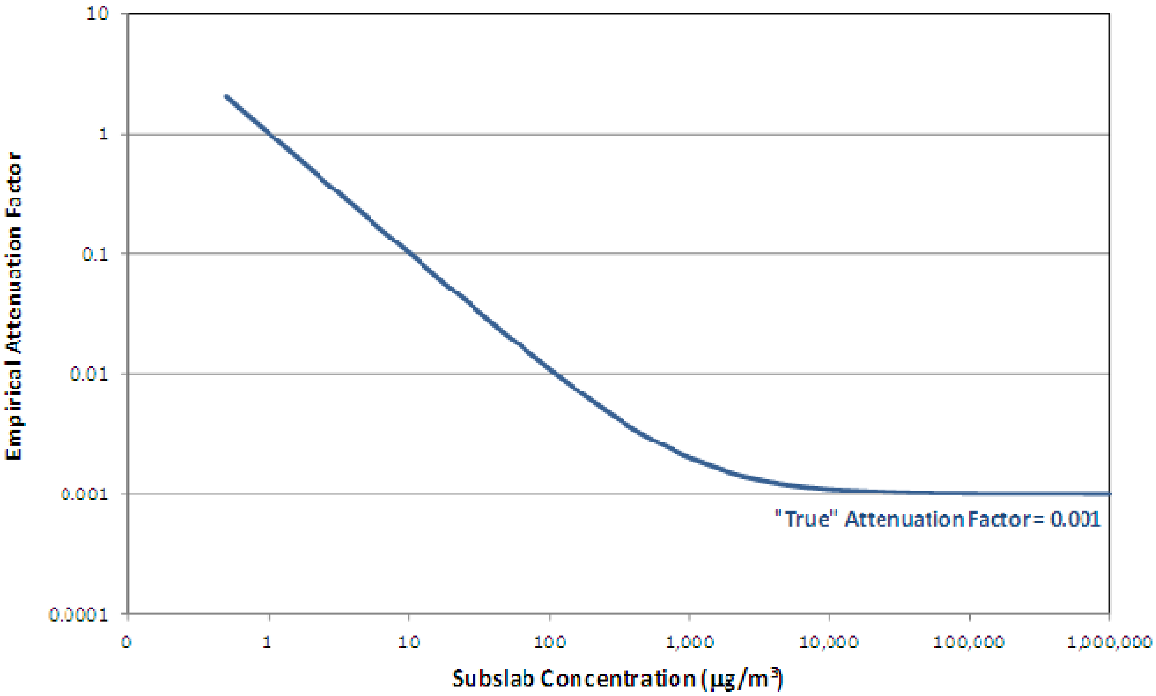

Figure 7b. Hypothetical case illustrating the influence of background sources on empirical attenuation factors.

The hypothetical background indoor air concentration is 1 µg/m^3 and the hypothetical "true" vapor intrusion building attenuation factor is 0.001.

This analysis demonstrates that attenuation factors representing vapor intrusion may be best observed when indoor air concentrations are greater than background indoor air levels and/or when subslab soil gas concentrations are high. Similar relationships are expected when comparing observed indoor air concentrations to other subsurface vapor data (e.g., equilibrium vapor concentrations corresponding to groundwater concentrations and exterior soil gas concentrations). The evaluations presented in Sections 4.0 and 5.0 of this report are based on these conceptual approaches.

3.4 Handling Data Below Reporting Limits

Concentrations of chemicals less than a quantitative threshold limit may be reported as below a given reporting limit (U-qualified data) or as estimated concentrations of authentic detections less than the reporting limit (J-qualified data). Indoor air concentrations below reporting limits (U-qualified and J-qualified values) were included in the statistical evaluation of attenuation factors. These low-level indoor air concentrations were included in the evaluation because, when they occur in buildings overlying subsurface vapor sources, they may represent cases where significant attenuation is occurring along the vapor intrusion pathway. For such situations, the corresponding attenuation factor would be very low and exclusion of these data would tend to bias the attenuation factor distributions upward (i.e., toward larger-valued attenuation factors that suggest less dilution is occurring). In contrast, subsurface data with concentrations less than the reporting limit were excluded from the evaluation because these data are considered to represent cases where the chemical is not present under the building or is present at levels unlikely to result in a detectable indoor air concentration via the vapor intrusion pathway.

A number of sites in the vapor intrusion database have substantial proportions (i.e., greater than 15 percent) of the indoor air concentrations reported as below a reporting limit (see **Table 3**). Numerous older EPA guidance documents recommend substituting one-half the reporting limit, particularly if less than 15 percent of the data set is below the reporting limit (e.g., EPA, 1998). However, studies by Helsel (2005b, 2006) and more recent EPA reports (e.g., Singh et al., 2006) have shown that substitution of such fixed values may lead to biases in the resulting concentration statistics.

Because the database includes sites that have substantial proportions of the indoor air concentrations reported as below a reporting limit (i.e., greater than 15 percent) (see **Table 3**), this report uses the Kaplan-Meier method, based on the findings of Helsel (2005b, 2006), to estimate descriptive statistics. This method is a robust non-parametric method capable of considering data sets with substantial proportions of data below reporting limits, as well as multiple reporting limits and J-qualified values. The Kaplan-Meier method assigns a percentile value to each detected observation, starting at the largest value and working down, on the basis of the number of observations above and below that observation. Percentiles are not assigned to data that are below reporting limits, but these data affect the percentiles calculated for the observations that are above reporting limits.

The Kaplan-Meier statistics presented in this report were generated using a spreadsheet provided by Helsel (2005a), which was expanded to include 5th and 95th percentile calculations and modified to enable its use within the MS Excel spreadsheet that holds EPA's vapor intrusion database. For all sample results reported as below the reporting limit, the value of the reporting limit was input in the concentration field, as recommended by Helsel (2005a), and the data were flagged as being below the reporting limit. Because data from multiple laboratories and various analytical methods are included in the database, reporting limits for any given chemical in the database may vary by more than an order of magnitude for a given sample media. For all detected samples, including J-qualified data, the actual sample concentration (or mean of duplicate values) was recorded in the concentration field. Attenuation factors based on indoor air concentrations below reporting limits were treated in the same way as concentrations below reporting limits when calculating statistics: they were flagged in the database as being less than the attenuation factor calculated using the indoor air sample reporting limit and statistically analyzed using the Kaplan-Meier method.

4.0 Attenuation Factor Screening: Criteria and Results

Several screening criteria were used to generate subsets of the database that could be used to calculate empirical attenuation factors for which subsurface sources of vapors (rather than background sources) were likely to be the principal contributor to the chlorinated VOCs observed in residential indoor air. This section describes the screening criteria and presents the distributions of attenuation factors that resulted from the screening.

EPA's vapor intrusion database was screened to extract a subset of data containing only those attenuation factors calculated for chlorinated hydrocarbons (CHCs) measured in residential settings (**CHCs in Residences Screen**). This subset of data comprises the majority of the database and is the focus of this document. The database was further screened to exclude subsurface concentrations below reporting limits from the attenuation factor analysis (**Subsurface Concentration Screen**) to focus on the data of site-specific concern for vapor intrusion. Indoor air concentrations potentially influenced by background sources were identified by evaluating field notes and data consistency measures described below (**Data Consistency Screen**); these data also were excluded from the attenuation factor analysis. These three screens are collectively termed the **Baseline Screens** for the purposes of this analysis. The data comprising the **Baseline Screens Data Set** were then further screened, by one of two approaches, to identify vapor intrusion attenuation factors minimally impacted by background indoor air concentrations, as described above in Section 3.3. These two approaches were:

- exclude indoor air data with concentrations below the 90th percentile of background levels (**Indoor Air Screen**); or
- exclude subsurface data with very low vapor concentrations (**Source Strength Screen**).

Each of these five screening criteria is discussed in greater detail in the following sub-sections.

Table 4 provides a summary of the number of attenuation factors remaining after each successive data-screening step. The data remaining after either the **Indoor Air Screen** or **Source Strength Screen** are considered a sufficiently large data set to support analysis of the attenuation factors. Note that the **Source Strength Screen** retained a larger number of subslab soil gas, groundwater, and crawlspace attenuation factors, compared with the **Indoor Air Screen**.

Table 4. Number of attenuation factors remaining after each successive data-screening step.

Attenuation Factor Type	EPA VI Database	Baseline Screens CHCs in Residences Screen[a]	 Subsurface Concentration Screen[b]	 Data Consistency Screen[c]	Indoor Air Screen[d,e]	Source Strength Screen[d.f]
Groundwater to indoor air	1,021	952	920	810	634	774
Exterior soil gas to indoor air	235	213	202	176	89	106
Subslab soil gas to indoor air	1,582	1,231	1,207	767	320	431
Crawlspace to indoor air	91	91	90	51	41	45
Total	2,929	2,487	2,419	1,804	1,084	1,356

[a] **CHCs in Residences Screen**: Subset of database remaining after screening chemicals other than chlorinated hydrocarbons (CHCs) measured in residential settings.

[b] **Subsurface Concentration Screen**: Subset of **CHCs in Residences Screen Data Set** remaining after further screening out subsurface concentrations less than reporting limits (RLs).

[c] **Data Consistency Screen**: Subset of **Subsurface Concentration Screen Data Set** remaining after further screening out samples for which field notes indicate the presence of indoor ("background") sources of VOCs, indoor air concentrations are greater than the corresponding subsurface concentration, or attenuation factors for an individual chemical are inconsistent with the attenuation factors for other chemicals reported for the same pair of samples. The resulting data are also referred to as the **Baseline Screens Data Set** in the remainder of this document.

[d] Counts reflect application of either the **Indoor Air Screen** or the **Source Strength Screen**.

[e] **Indoor Air Screen**: Subset of **Baseline Screens Data Set** remaining after further screening out indoor air concentrations less than the 90th percentile of background levels or less than the RLs (if RL is greater than the 90th percentile). The rationale for using these background levels is described in Section 4.4.

[f] **Source Strength Screen**: Subsets of **Baseline Screens Data Set** remaining after further screening out source-strength concentrations less than certain multipliers of the 90th percentile of background levels. The selected multipliers are 1,000X for groundwater, 50X for exterior soil gas, 50X for subslab soil gas, and 1X for crawlspace.

4.1 Screening for Chlorinated Hydrocarbons and Residential Settings—CHC in Residences Screen

EPA's vapor intrusion database was screened to focus on those attenuation factors calculated for CHCs in residential settings, which are the focus of this report. This included screening out any chemicals labeled as a PHC and any buildings labeled as "commercial," "commercial/residential," "residential/commercial," and "multi-use." After this screening step, there remained a total of 2,487 attenuation factors: 952 paired groundwater and indoor air concentrations, 213 paired exterior soil gas and indoor air concentrations, 1,231 paired subslab soil gas and indoor air concentrations, and 91 paired crawlspace and indoor air measurements (as shown in **Table 4**). These data comprise the majority (85 percent) of EPA's vapor intrusion database: 93 percent of the paired groundwater and indoor air measurements, 90 percent of the paired exterior soil gas and indoor air measurements, 78 percent of the paired subslab soil gas and indoor air measurements, and 100 percent of the paired crawlspace and indoor air measurements. The subset of data is referred to as the CHC in **Residences Screen Data Set**.

4.2 Identifying Chemicals of Site-Specific Concern—Subsurface Concentration Screen

Subsurface samples with concentrations less than the reporting limit were flagged and excluded from further analysis. For purposes of this document, such low-level subsurface concentrations were considered to represent cases where the chemical either is not present under the building or is present at levels unlikely to result in a detectable indoor air concentration via the vapor intrusion pathway. Nevertheless, the same chemical may be present in the indoor air of an overlying building due to indoor (background) sources, which would lead to an artificially high attenuation factor. Thus, subsurface concentrations less than the reporting limits were not used in the evaluation of attenuation factors. Also screened out were any repeated results for a given medium, repeated as an artifact of the construction of the spreadsheet in which multiple subsurface samples may be tied to a building with only one subslab soil gas or indoor air sample (e.g., exterior soil gas samples taken adjacent to all four sides of a building). After the "subsurface concentration" screening was applied to the **CHC in Residences Screen Data Set**, there remained a total of 2,419 individual attenuation factors: 920 paired groundwater and indoor air concentrations, 202 paired exterior soil gas and indoor air concentrations, 1,207 paired subslab soil gas and indoor air concentrations, and 90 paired crawlspace and indoor air concentrations (as shown in **Table 4**). This subset of data is referred to as the **Subsurface Concentration Screen Data Set**.

4.3 Identifying the Presence of Indoor Sources of VOCs—Data Consistency Screen

Several methods were used to identify indoor air data and, therefore, attenuation factors likely to be unbiased by background contributions to the indoor air concentrations. These methods included:

- reviewing field sampling notes,
- reviewing sample pairs with attenuation factors greater than one (i.e., indoor air concentrations greater than subsurface concentrations), and
- evaluating the consistency of attenuation factors for different chemicals in a given pair of indoor and subsurface samples.

Field Sampling Notes:

Indoor air samples taken in buildings for which field notes indicated the presence of indoor (background) sources of organic chemicals (such as open solvent or gas containers) or recent significant use of chemicals (such as paint or new carpets) were deemed likely to be biased by background sources for certain compounds. Paired samples in the database with information indicating the possibility of such indoor sources were flagged and excluded from further analysis.

Attenuation Factors > 1:

Because of the attenuation and dilution that occur as vapors migrate from the subsurface upward through soil and into a ventilated building, indoor air concentrations resulting from vapor intrusion are generally expected to be less than the subsurface vapor concentration. Consequently, vapor intrusion attenuation factors are expected to be less than one. Attenuation factors equal to or greater than one may be observed for a number of reasons, however. Most commonly, indoor air concentrations of VOCs that are greater than their corresponding subsurface vapor concentrations suggest that background sources may be influencing the attenuation factor. Where background sources are present, subslab soil gas may contain volatile substances simply because buildings "breathe" air into and out of the subsurface due to fluctuations in building pressurization. In these cases, the subslab soil gas concentrations are not considered representative of subsurface source vapor concentrations and are not an indicator of vapor intrusion. Analytic errors may also result in attenuation factors greater than one. Vapor intrusion data corresponding to calculated attenuation factors greater than one were reviewed and compared with other data collected in the same building to determine if indoor (background) sources were likely contributing to the indoor air concentration; if so, these paired data were excluded from further analysis and the reason for the exclusion was described in a comment field in the database.

Vapor intrusion data where subslab soil gas concentrations exceeded the calculated groundwater vapor concentrations tied to a building also were reviewed and compared with nearby information to determine if the groundwater data were not representative of conditions under the building (e.g., where very steep concentration gradients are present). Because of the attenuation that occurs by transport through soil, subslab soil gas concentration is expected to be less than the vapor concentration corresponding to the groundwater concentration. Groundwater data deemed unrepresentative were flagged as such and were excluded from further analysis.

In some cases, because of the natural and independent variability in indoor air and subsurface vapor concentrations and non-steady-state conditions, an attenuation factor greater than one may represent actual conditions at the time of sampling. In these cases, the indoor air concentrations may erroneously be attributed to background sources. There may also be cases in which the measured exterior soil gas concentrations are not representative of source concentrations contributing to vapor intrusion, even though the subslab soil gas or indoor air concentrations may be smaller. Errors of this sort may be minimized by developing a sound conceptual model of vapor source(s) and migration and collecting a sufficient number of well-located samples to characterize the spatial distribution and temporal variability in the subsurface vapor and indoor air concentrations, in accordance with the conceptual model.

Consistency of Attenuation Factors for Different Chemicals in Paired Samples:

Background influences may also be determined by evaluating the consistency in attenuation factors among chemicals if more than one chemical is reported for a given sample (and we can justifiably assume identical distributions of both chemicals in the subsurface so they have equal access to openings in the building envelope). Attenuation factors would be expected to be similar for chemicals with similar vapor fate and transport properties, which is the case for many chlorinated VOCs.[5] For example, **Figure 8a** shows the similarity in attenuation factors for several chemicals analyzed in a single pair of subslab soil gas and indoor air samples from a building where background influences are apparently not present or are insignificant. In contrast, **Figure 8b** shows significant dissimilarity in attenuation factors among four substances in a pair of samples for a given building, which suggests that background sources have influenced the measured indoor air concentrations for PCE and Freon (an additional line of evidence is that both PCE and Freon are known as common background contaminants). Attenuation factors considered to be inconsistent (invalid) using this approach were flagged and excluded from further analysis.

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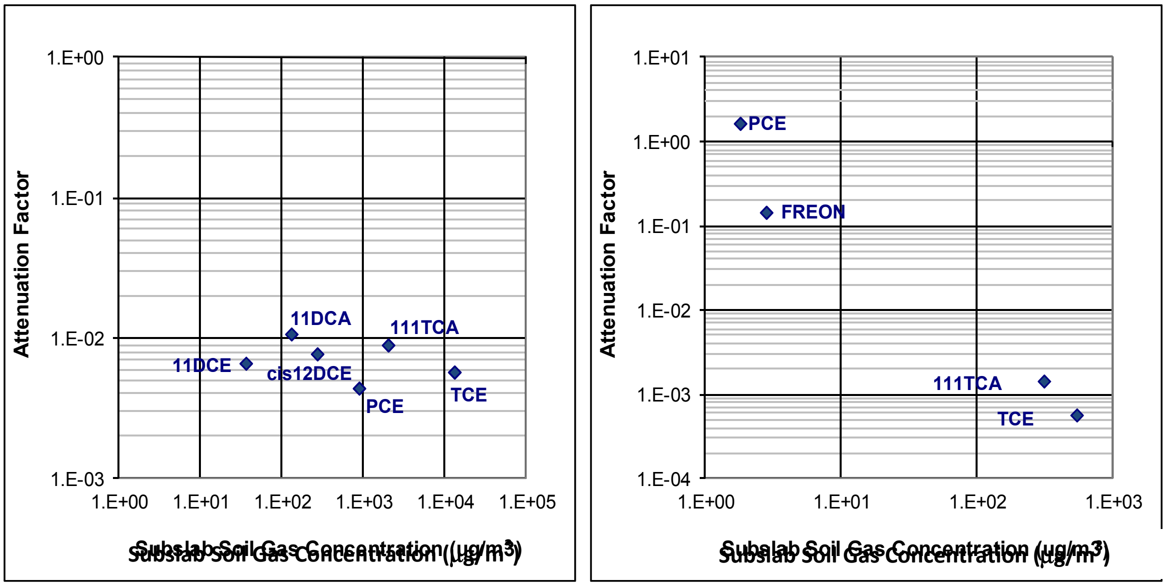
[5] Because of analytical uncertainty, particularly for chemicals with concentrations near the reporting limit, and because of differences in the diffusion coefficients of chemicals, the calculated ratios are not expected to be exactly the same value for each chemical. Rather, a propagation of error analysis suggests the attenuation factors for chemicals with similar fate and transport properties are expected to be within a factor of five to ten of each other. Thus, empirical attenuation factors among a group of recalcitrant substances that differ by more than an order of magnitude (comparing largest to smallest) are probably indicative of bias by background sources and may not be representative of the site-specific vapor intrusion pathway.



(a) Residence 002 **(b) Residence 005**

Note: 11DCA = 1,1-dichloroethane; 11DCE = 1,1-dichloroethylene; 11DCE = 1,1-dichloroethylene; cis12DCE = cis-1,2-dichloroethylene; FREON = 1,1,2-trichloro-1,2,2-trifluoroethane; PCE = tetrachloroethylene; 111TCA = 1,1,1-trichloroethane; TCE = trichloroethylene

Figure 8. Empirical attenuation factors for individual chemicals in two buildings at the Endicott, NY, site.

(a) Because the attenuation factors are similar for all chemicals for Residence 002, little or no background influence is suggested for this building; (b) The attenuation factors for PCE and Freon in Residence 005 are significantly higher than those for 111TCA and TCE, suggesting there is background influence on PCE and Freon. The attenuation factors are similar for 111TCA and TCE in Residence 005.

After the screening criteria described above (field notes indicating background sources, attenuation factors greater than one, and inconsistent attenuation factors), the previous screening of subsurface concentrations less than RLs, and screening to focus on CHCs in residences, there remained 810 paired groundwater and indoor air concentrations, 176 paired exterior soil gas and indoor air concentrations, 767 paired subslab soil gas and indoor air concentrations, and 51 paired crawlspace and indoor air concentrations (as shown in **Table 4**). This subset of data remaining after the **Data Consistency Screen** is referred to as the **Baseline Screens Data Set** in the remainder of this document, because the three screening criteria described above (Sections 4.1, 4.2, and 4.3) are collectively referred to as the Baseline Screens.

4.4 Identifying Empirical Attenuation Factors Minimally Biased by Background Contributions

Two approaches were separately employed to further identify empirical attenuation factors minimally biased by background contributions to indoor air concentrations. As described in Section 3.3, attenuation factors representing vapor intrusion may be best observed when indoor air concentrations are greater than background levels and/or when source (e.g., exterior or subslab soil gas) concentrations are high. Section 4.4.1 describes an analysis focusing on identifying indoor air concentrations greater than background levels, and Section 4.4.2 describes an analysis focusing on high subsurface source strength concentrations.

4.4.1 Identifying Indoor Air Concentrations Above Typical Background Levels—Indoor Air Screen

The **Baseline Screens Data Set** (i.e., the data remaining after applying the three **Baseline Screens** described above [Sections 4.1, 4.2, and 4.3]) was screened to identify indoor air concentrations greater than "typical" upper-bound levels of background indoor air concentrations. For the purposes of the attenuation factor analysis presented here, the median of the reported 90th percentiles of the background indoor air concentration distributions compiled in the Background Indoor Air report (EPA, 2011a) was selected to represent "typical" upper-bound levels of background indoor air concentrations, following the methodology described by Dawson and McAlary (2009). These values are presented in **Table 5**. The 90th percentile level was selected over the 95th percentile level because significantly more studies reported 90th percentiles than reported 95th percentiles. For sake of conciseness, the median of the reported 90th percentiles of background indoor air concentrations are referenced hereafter as "background." Note, however, this approach to screening does not imply that the 90th percentile background levels should be used for site-specific regulatory decision making.

The indoor air data with concentrations less than "background" were screened out as a means of ensuring there was a low likelihood that the indoor air concentrations could be from background (non-VI) sources and a high likelihood that the remaining attenuation factors were based on indoor air concentrations that are due to vapor intrusion (i.e., are not attributable to background sources). The theoretical foundation for this **Indoor Air Screen** is described in Section 3.3. This screening approach minimizes the influence of the second term on the right-hand side of Equations 3 and 4a by eliminating indoor air concentrations (C_{IA}) less than "background" ($C_{IA\text{-}BKGD}$) and considering only those indoor air concentrations that theoretically reflect only vapor intrusion (right-hand part of **Figure 7a**).

An advantage of this method of screening is that it focuses on the medium to which receptors are exposed. A disadvantage of the method is that empirical attenuation factors calculated based on indoor air concentrations that are low, yet truly arise only from vapor intrusion, are removed from the analysis, in which case the attenuation factors resulting from the **Indoor Air Screen Data Set** may be biased high. The data set may also be biased high by the inclusion of attenuation factors calculated using indoor air concentrations that are higher than the "background" levels used in this analysis, yet still represent contributions from background sources.

After application of the **Indoor Air Screen**, there remained 634 paired groundwater and indoor air concentrations, 89 paired exterior soil gas and indoor air concentrations, 320 paired subslab soil gas and indoor air concentrations, and 41 paired crawlspace and indoor air concentrations (as shown in **Table 4**). This subset of data is referred to as the **Indoor Air Screen Data Set**.

Table 5. Upper-end background indoor air concentrations of common VOCs measured in North American residences between 1990 and 2005 used to screen EPA's vapor intrusion database.

Compound	Median of 90th Percentile Conc.[a] (µg/m^3)	N[b]
Benzene	9.5	11
Carbon tetrachloride	0.8	5
Chloroform	4.0	9
Dichloroethane, 1,1-	<RL	2
Dichloroethane, 1,2-	0.1	7
Dichloroethylene, 1,1-	0.8	2
Dichloroethylene, cis 1,2-	<RL	3
Ethylbenzene	8.9	7
Methyl tert-butyl ether (MTBE)	38	4
Methylene chloride	10.5	8
Tetrachloroethylene	3.8	10
Toluene	54	9
Trichloro-1,2,2-trifluoroethane, 1,1,2- (Freon 113)	1.8	3
Trichloroethane, 1,1,1-	3.1	8
Trichloroethylene	0.5	9
Vinyl chloride	0.01	4
Xylene, m/p-	21	9
Xylene, o-	10.8	9

[a] Data source is the Background Indoor Air Report (EPA, 2011a).

[b] N = Number of studies reporting the 90th percentile.

4.4.2 Identifying Appropriately High Subsurface Vapor Concentrations—Source Strength Screen

The **Baseline Screens Data Set** (i.e., the data remaining after applying the **Baseline Screens** described above [Sections 4.1, 4.2, and 4.3]) was screened to identify empirical attenuation factors likely to represent the effects of vapor intrusion with minimal bias from background contributions. This screening approach uses a multiplier of "background" to screen the subsurface concentrations. In other words, the data set was screened by selecting those subsurface concentrations that exceed "background" by a specific multiplicative factor, for example 10, 50, 100, 500, or 1,000. The theoretical foundation for the **Source Strength Screen** is described in Section 3.3. This screening approach minimizes the influence of the second term on the right-hand side of Equations 3 and 4a by eliminating smaller source concentrations (C_{SV}) and considering only those source concentrations that theoretically reflect only vapor intrusion (right-hand part of **Figure 7b**).

For this analysis, several multipliers of "background" were applied and statistically evaluated as described below for each medium. The multipliers ultimately selected for screening the subsurface concentrations are 1,000X for groundwater, 50X for exterior soil gas, 50X for subslab soil gas, and 1X for crawlspace vapor, because these provide data sets that appear minimally biased by background contributions to indoor air concentrations, yet maximize the amount of data remaining.

An advantage of the source-strength screening approach is that it minimizes the influence of background, while still allowing consideration of indoor air concentrations that are within the background range, but which may, in fact, be due to vapor intrusion. Another potential advantage of the source-strength screening approach is that it may remove non-representative data for which the sampling results are biased (for example, due to leakage around sampling ports). A disadvantage of the source-strength screening approach is that the set of attenuation factors remaining may be biased low when low source-strength data are removed in cases where vapor intrusion is occurring and where the indoor air data are not influenced by background.

After application of the **Source Strength Screen** using the selected multipliers, there remained 774 paired groundwater and indoor air concentrations, 106 paired exterior soil gas and indoor air concentrations, 431 paired subslab soil gas and indoor air concentrations, and 45 paired crawlspace and indoor air concentrations (as shown in **Table 4**). This subset of data is referred to as the **Source Strength Screen Data Set**.

4.5 Application of Screening Criteria to the Database

The primary purpose of employing the screening criteria described above is to generate subsets of the database that can be used to calculate empirical attenuation factors for which subsurface sources of vapors (rather than background sources) were likely to be the principal contributor to the chlorinated VOCs observed in residential indoor air. In summary, a total of five screening approaches were evaluated:

- Three **Baseline Screens** applied in combination:
  - **CHCs in Residences Screen**: extract the subset of data containing only those attenuation factors calculated for CHCs measured in residential settings, the data of primary interest for this document.
  - **Subsurface Concentration Screen**: in addition exclude subsurface concentrations below the reporting limits from the attenuation factor analysis to focus on the data of site-specific concern for vapor intrusion.
  - **Data Consistency Screen**: in addition exclude indoor air concentrations potentially influenced by background sources by evaluating field notes and data consistency measures.
- Two additional screens applied separately:
  - **Indoor Air Screen**: exclude indoor air concentrations potentially influenced by background sources by excluding those with concentrations below "background" (see **Table 5**); or
  - **Source Strength Screen**: exclude indoor air concentrations potentially influenced by background sources by excluding lower subsurface vapor concentrations.

In this sub-section, the results of applying these screening approaches to the vapor intrusion database are evaluated and characterized using descriptive statistics, box-and-whisker plots, frequency plots, cumulative probability plots, and scatter plots. Descriptive order statistics—the 5th, 25th, 50th, 75th, and 95th percentiles—are calculated, using the Kaplan-

Meier method described earlier, for groundwater-, exterior soil gas-, subslab soil gas -, and crawlspace-to-indoor-air attenuation factors. The descriptive order statistics are plotted and analyzed using box-and-whisker plots (where the upper and lower edges of the box represent the 25th and 75th percentiles, respectively; the minimum and maximum values are shown on the whiskers below and above the box, respectively; and the median (50th percentile) is shown in the dark bar inside the box). The scatter plots are used to illustrate the impact of the various screening approaches on the actual data. Finally, the frequency and cumulative probability plots are used to visually assess the normality of the distribution of the data sets. The premise behind the use of the cumulative probability plots is that contributions to indoor air concentrations from subsurface sources through vapor intrusion and from background sources may be distinct populations, which may be distinguishable using this approach.

The descriptive statistics, box-and-whisker plots and the scatter plots, were generated using MS Excel's built-in graphical tools as each of the screening criteria was applied. The frequency plots were generated using MS Excel's built in data analysis tool. The cumulative probability plots were generated by plotting the attenuation factors sorted from smallest to largest on a log scale versus their normal scores (also called Z-scores), which indicate how many standard deviations a given value of the sorted attenuation factor distribution is above or below the mean of the distribution. The normal score is calculated by using MS Excel's NORMSINV function with the uniform order statistuc median as the input argument. The uniform order statistic median is calculated as follows (NIST, 2010):

$$U(i) = 1 - U(n) \text{ for } i = 1 \qquad \text{Equation 5a}$$

$$U(i) = (i - 0.3175)/(n + 0.365) \text{ for } i = 2, 3, ..., n - 1 \qquad \text{Equation 5b}$$

$$U(i) = 0.5^{(1/n)} \text{ for } i = n \qquad \text{Equation 5c}$$

The evaluation of subslab soil gas data is presented first, followed by the groundwater, exterior soil gas, and crawlspace data.

4.5.1 Subslab Soil Gas Data

The descriptive statistics and box-and-whisker plots generated by the spreadsheet version of the database for the subslab soil gas attenuation factors and screening criteria described above are shown in **Table 6** and **Figure 9**, respectively. Several multipliers of "background" were used to screen the indoor air or subslab soil gas concentrations in the **Baseline Screens Data Set**. Frequency plots illustrating the distributions resulting from applying the screening criteria are shown in **Figure 10**. The corresponding cumulative probability plots are shown in **Figure 11**.

Table 6. Descriptive statistics of subslab soil gas attenuation factor distributions after application of various database screens.

	Applied Database Screen								
Statistic	CHCs in Residences	Subsurface Concentration	Data Consistency	IA > Bkgd	SS > 10X Bkgd	SS > 50X Bkgd	SS > 100X Bkgd	SS > 500X Bkgd	SS > 1,000X Bkgd
Min	2.5E-05	2.5E-05	2.5E-05	9.6E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05
5%	6.2E-04	6.2E-04	4.7E-04	4.7E-04	3.9E-04	3.2E-04	3.0E-04	2.6E-04	2.5E-04
25%	2.7E-03	2.7E-03	2.0E-03	1.9E-03	1.7E-03	1.5E-03	1.3E-03	1.1E-03	1.1E-03
50%	1.3E-02	1.3E-02	6.2E-03	5.0E-03	3.9E-03	2.7E-03	2.5E-03	2.5E-03	2.5E-03
75%	2.3E-01	2.2E-01	3.0E-02	1.2E-02	9.3E-03	6.8E-03	6.3E-03	6.3E-03	5.8E-03
95%	1.5E+00	1.4E+00	5.3E-01	1.8E-01	5.2E-02	2.6E-02	2.0E-02	1.8E-02	1.5E-02
Max	1.3E+02	1.3E+02	9.6E-01	9.4E-01	9.4E-01	9.4E-01	9.4E-01	9.4E-01	9.4E-01
Mean	6.5E-01	6.5E-01	7.5E-02	3.6E-02	1.9E-02	9.2E-03	8.1E-03	8.2E-03	8.5E-03
StdDev	5.2E+00	5.3E+00	1.8E-01	1.1E-01	7.1E-02	5.0E-02	4.9E-02	5.8E-02	6.2E-02
95UCL	9.0E-01	9.0E-01	8.5E-02	4.6E-02	2.4E-02	1.3E-02	1.2E-02	1.4E-02	1.5E-02
No. of AFs	1,231	1,207	767	320	577	431	379	262	232
No. of AFs > RL	981	972	677	308	532	411	363	248	220
No. of AFs < RL	250	235	90	12	45	20	16	14	12
No. of sites	13	13	13	11	13	12	11	10	10

CHCs in Residences Screen: Subset of database remaining after screening chemicals other than CHCs measured in residential settings.

Subsurface Concentration Screen: Subset of **CHCs in Residences Data Set** remaining after further screening out subsurface concentrations less than RLs.

Data Consistency Screen: Subset of **Subsurface Concentration Screen Data Set** remaining after further screening out samples for which field notes indicate the presence of indoor (background) sources of VOCs, indoor air concentrations are significantly greater than the corresponding subsurface concentration, or attenuation factors for an individual chemical are inconsistent with the attenuation factors for other chemicals reported for the same pair of samples. The resulting data are also referred to as the **Baseline Screens Data Set** in the remainder of this document.

Indoor Air Screen (IA > Bkgd): Subset of **Baseline Screens Data Set** remaining after further screening out indoor air concentrations less than “background” levels or less than the RLs (if RL is greater). The rationale for using the “background” levels is described in Section 4.4.

Source Strength Screen (SS > 10X Bkgd, SS > 50X Bkgd, SS > 100X Bkgd, SS > 500X Bkgd, SS > 1,000X Bkgd): Subsets of the Baseline Screens Data Set remaining after further screening out subslab soil gas concentrations less than certain multipliers (10, 50, 100, 500, and 1,000) of “background” levels.

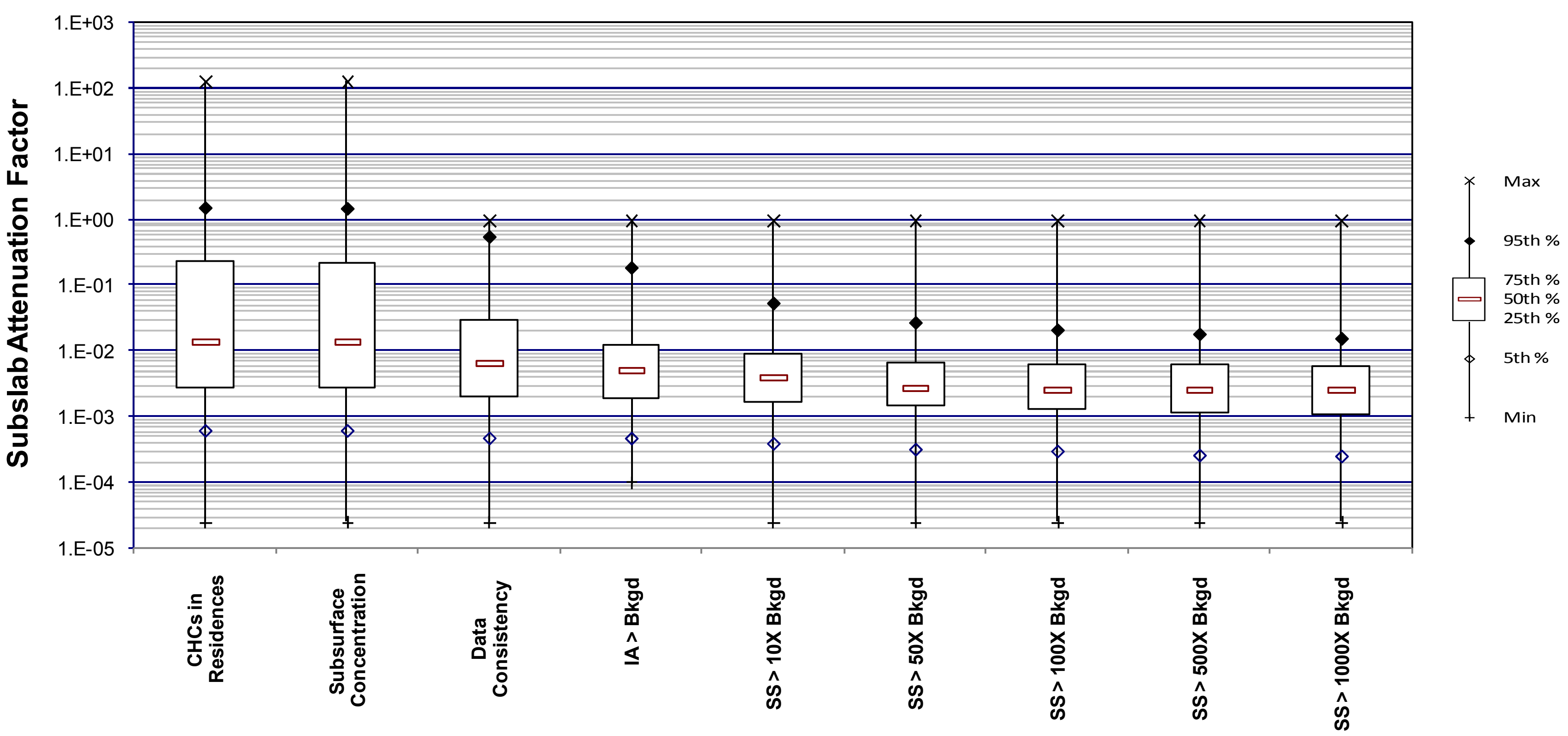


Figure 9. Box-and-whisker plots summarizing subslab soil gas attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 6 and described in Sections 4.1 through 4.4.)

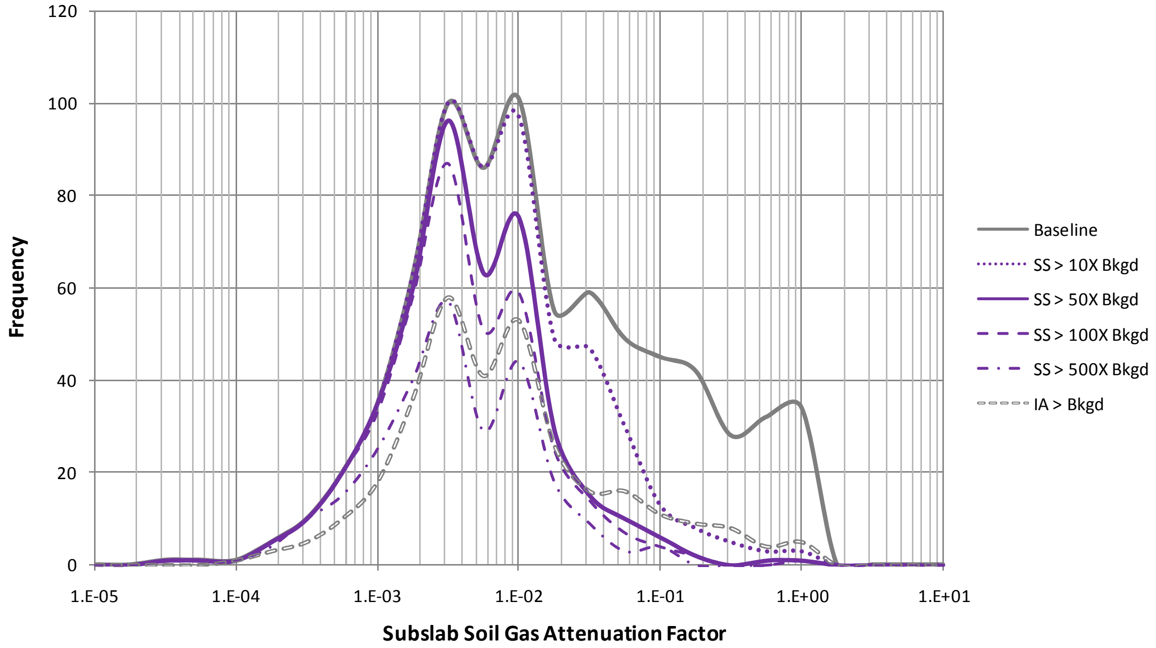


Figure 10. Frequency plots summarizing subslab soil gas attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 6 and described in Sections 4.1 through 4.4.)

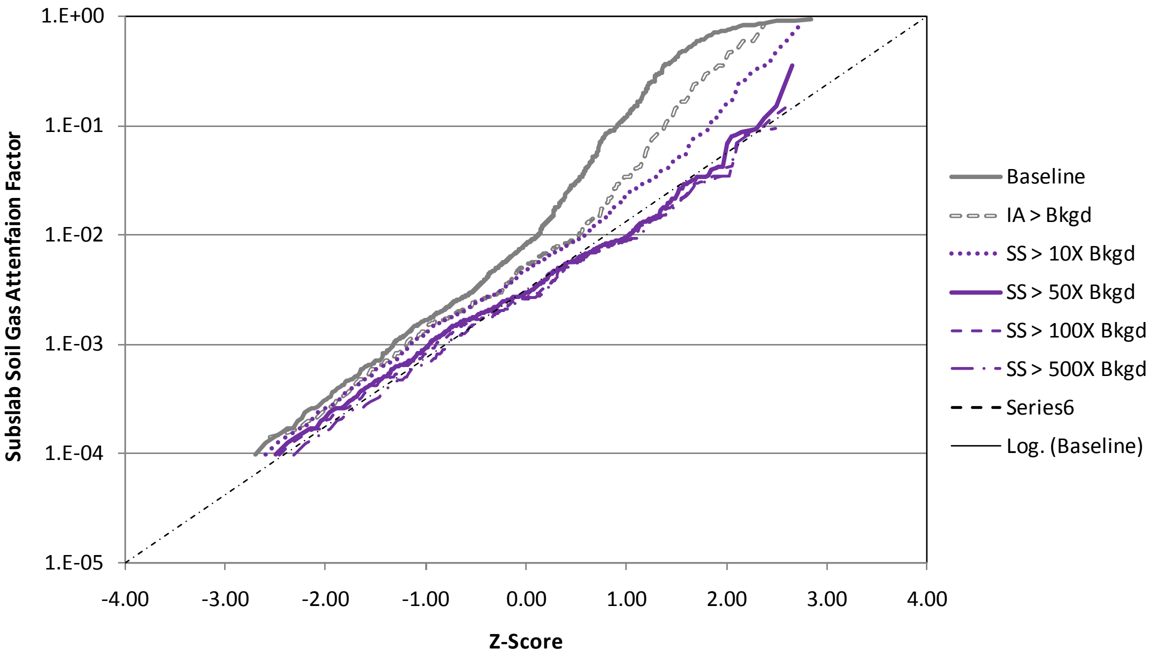


Figure 11. Cumulative probability plots summarizing subslab soil gas attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 6 and described in Sections 4.1 through 4.4.)

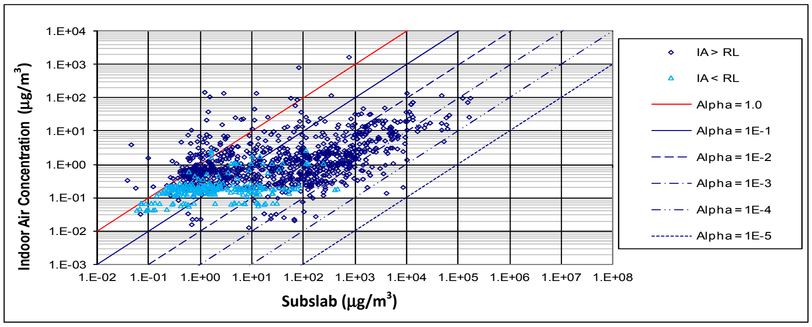
Figures 10 (frequency plot) and **11** (cumulative probability plot) show that when the three **Baseline Screens** are applied (see thick gray line), a bi- or tri-modal distribution results, indicating the potential influence of background sources on the empirical subslab soil gas attenuation factors. Further screening the **Baseline Screens Data Set** using the **Indoor Air Screen** improves the distribution (see dashed line marked IA > Bkgd), but the additional modes are not completely eliminated. On the other hand, application of the **Source Strength Screen** produces "cleaner" distributions, in that the frequency plots more closely appear "normal" and the cumulative probability plots more closely approach linearity. This analysis indicates that **Source Strength Screen** more effectively minimizes the influence of background contributions to indoor air than does the **Indoor Air Screen**. The attenuation factor distributions that remain after applying the **Source Strength Screen** are closer approximations to lognormal distributions and exhibit less of the bimodal distortion that may be induced by background contributions to indoor air. Similar results were obtained by Song et al. (2011).

As a sensitivity analysis, the **Indoor Air Screen** was applied in combination with the **Source Strength Screen** (statistics not shown in **Table 6**). This resulted in less than a 30 percent change in the values of each descriptive statistic and no change in the 95th percentile value when rounded to one significant figure, yet substantially reduced the number of attenuation factors in the data set.

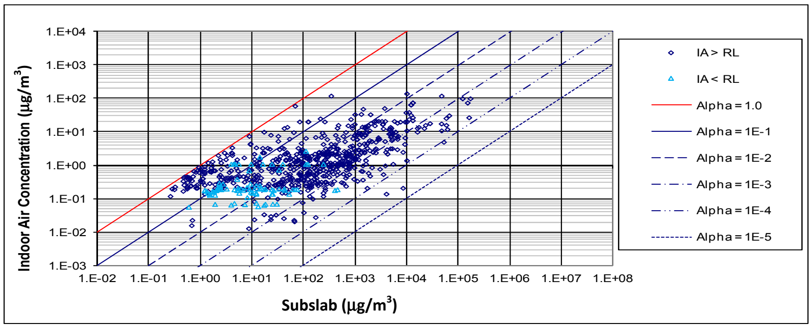
As a result of the foregoing analyses, a **Source Strength Screen** with a multiplier of 50 times "background" (see solid line marked **SS > 50X Bkgd**) is the best screening criterion for minimizing the influence of background sources on the data set of subslab soil gas attenuation factors. This **Source Strength Screen** also has the advantage of retaining a greater number of attenuation factors than does the **Indoor Air Screen**. The source-strength screening criterion of 50 times the "background" levels is used in the remainder of this report to further evaluate the subslab soil gas attenuation factors, as discussed in Section 5.0.

These results can be further illustrated by examining scatter plots of indoor air versus subslab soil gas concentrations after the various screening criteria are applied and comparing them to the scatter plot for the hypothetical case described in Section 3.3 and illustrated in **Figure 7a**. **Figure 12a** plots indoor air concentration versus subslab soil gas concentration for the subset of data remaining after applying the **CHCs in Residences Screen**. **Figure 12b** shows the subset of data remaining after further applying the **Subsurface Concentration** and **Data Consistency Screens** and thus represents the data set remaining after applying the three **Baseline Screens**. **Figure 12c** plots the data set remaining after applying the **Indoor Air Screen** to the **Baseline Screens Data Set**. **Figure 12d** plots the data set remaining after applying the **Source Strength Screen** (50X Background) to the **Baseline Screens Data Set**. Comparing these plots to **Figure 7a** indicates that the relationships are similar to those described for the hypothetical case, albeit with substantial variability because the scatter plots represent data from multiple buildings within a site and/or buildings from multiple sites where the observed indoor air and subslab soil gas concentrations are likely subject to substantial spatial and temporal variability. **Figure 12a** shows a "plateau" in the data at low indoor air concentrations and low subslab soil gas concentrations, as expected and as shown in the hypothetical case illustrated in **Figure 7a**. **Figure 12b** depicts the considerable benefit derived from the **Baseline Screens**, because the data distribution better approximates a linear relationship between indoor air and subslab soil gas concentrations. When indoor air concentrations below "background" are filtered out (**Indoor Air Screen—Figure 12c**) or when only high source-strength concentrations are included (**Source Strength Screen—Figure 12d**), the data distributions develop a more defined positive slope, with the "cleanest" results (clearer linearity and greater data retention) using the **Source Strength Screen**.

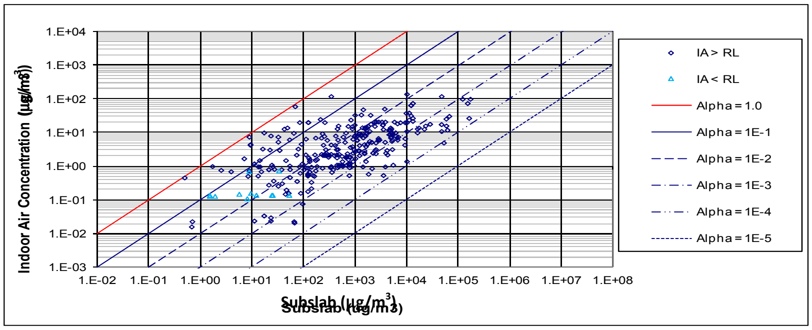
a) CHCs in Residences Data Set:



b) Baseline Data Set:



c) Indoor Air Screen Data Set (IA > Bkgd):



d) Source Strength Screen Data Set (SS > 50X Bkgd):

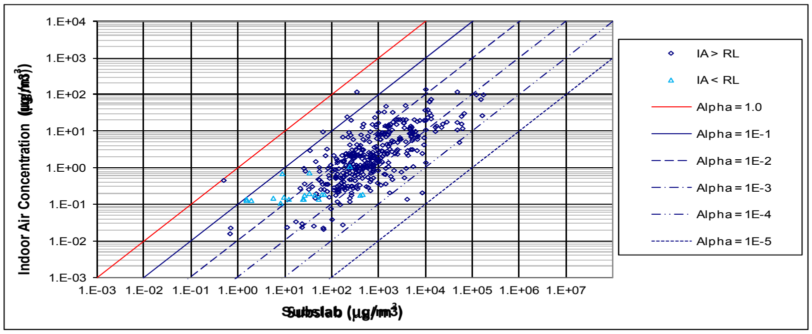


Figure 12. Scatter plots of paired indoor air and subslab soil gas concentrations for CHCs and residential buildings in EPA's vapor intrusion database after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 6 and described in Sections 4.1 through 4.4.)

Comparing the descriptive statistics for the **Indoor Air Screen Data Set** (IA > Bkgd) and the selected **Subsurface Source Screen Data Set** (SS > 50 X Bkgd) in **Table 6** and **Figure 9** shows that the attenuation factors remaining after the **Indoor Air Screen** tend to be greater than those remaining after the **Source Strength Screen**, particularly at the upper ends of the distributions. The 95th and 75th percentile values for the **Indoor Air Screen Data Set** are greater by factors of approximately seven and two times, respectively, than the 95th and 75th percentile values for the selected **Source Strength Screen Data Set**. The median (50th percentile) value for the **Indoor Air Screen Data Set** is approximately two times that for the selected **Source Strength Screen Data Set** (SS > 50 X Bkgd), and the 5th and 25th percentiles are approximately equal for the two data sets. This result was anticipated, as described in Section 4.4.2, because the **Indoor Air Screen** emphasizes higher indoor air concentrations regardless of the paired subslab soil gas concentrations, whereas the **Source Strength Screen** emphasizes higher subslab concentrations regardless of the paired indoor air concentrations. Thus, with the **Indoor Air Screen**, some of the remaining higher indoor air concentrations may be paired with relatively low subslab soil gas concentrations, resulting in relatively high attenuation factors, whereas with the **Source Strength Screen**, some of the remaining higher subslab soil gas concentrations may be paired with relatively low indoor air concentrations, resulting in relatively small attenuation factors.

4.5.2 Groundwater Data

The descriptive statistics and box-and-whisker plots generated for the groundwater attenuation factors and the screening criteria described above are shown in **Table 7** and **Figure 13**, respectively. Several multipliers of "background" were used to screen the indoor air or subsurface vapor concentrations in the Baseline Screens Data Set. Frequency plots and cumulative probability plots illustrating the distributions resulting from applying the screening criteria are shown in **Figures 14** and **15**, respectively. The corresponding scatter plots are shown in **Figure 16**.

Applying similar reasoning as for the subslab soil gas data (i.e., the screening criteria that result in frequency plots most closely appearing "normal" and cumulative probability plots most closely approaching linearity), a **Source Strength Screen** with a multiplier of 1,000 times "background" (see solid line marked GW > 1,000X Bkgd) is the best screening criterion for minimizing the influence of background sources on the data set of groundwater attenuation factors. This **Source Strength Screen** also has the advantage of retaining a greater number of attenuation factors than does the **Indoor Air Screen**. The source-strength screening criterion of 1,000 times "background" is used in the remainder of this report to further evaluate the groundwater attenuation factors, as discussed in Section 5.0.

As a sensitivity analysis, the **Indoor Air Screen** was applied in combination with the **Source Strength Screen** (statistics not shown in **Table 7**). This resulted in less than a 30 percent change in the values of each descriptive statistic and no change in the 95th percentile value when rounded to one significant figure, yet it substantially reduced the number of attenuation factors in the data set.

Table 7. Descriptive statistics of groundwater attenuation factor distributions after application of various database screens.

	Applied Database Screen							
Statistic	**CHCs in Residences**	**Subsurface Concentration**	**Data Consistency**	**IA > Bkgd**	**GW > 100X Bkgd**	**GW > 500X Bkgd**	**GW > 1,000X Bkgd**	**GW > 5,000X Bkgd**
Min	1.0E-07	1.0E-07	1.0E-07	8.6E-07	1.0E-07	1.0E-07	1.0E-07	1.0E-07
5%	3.6E-06	3.6E-06	3.7E-06	7.6E-06	3.7E-06	3.7E-06	3.6E-06	3.7E-06
25%	2.7E-05	2.7E-05	2.4E-05	3.3E-05	2.4E-05	2.4E-05	2.3E-05	2.3E-05
50%	9.2E-05	9.1E-05	7.7E-05	1.0E-04	7.6E-05	7.6E-05	7.4E-05	7.2E-05
75%	3.1E-04	3.1E-04	2.2E-04	2.6E-04	2.2E-04	2.1E-04	2.0E-04	1.9E-04
95%	2.5E-03	2.3E-03	1.3E-03	1.5E-03	1.2E-03	1.2E-03	1.2E-03	1.0E-03
Max	7.4E-02	7.4E-02	7.4E-02	7.4E-02	4.3E-02	4.3E-02	2.1E-02	2.1E-02
Mean	8.2E-04	7.3E-04	5.6E-04	6.8E-04	4.0E-04	3.5E-04	2.8E-04	2.5E-04
StdDev	4.1E-03	3.9E-03	3.9E-03	4.4E-03	2.2E-03	1.8E-03	1.0E-03	9.7E-04
95UCL	1.0E-03	9.4E-04	7.8E-04	9.7E-04	5.3E-04	4.6E-04	3.4E-04	3.1E-04
Count All	952	920	810	634	806	803	774	715
Count >RL	887	875	768	634	766	764	743	697
Count <RL	65	45	42	0	40	39	31	18
No. of sites	25	25	24	23	24	24	24	23

CHCs in Residences Screen: Subset of database remaining after screening chemicals other than CHCs measured in residential settings.

Subsurface Concentration Screen: Subset of **CHCs in Residences Data Set** remaining after further screening out subsurface concentrations less than RLs.

Data Consistency Screen: Subset of **Subsurface Concentration Screen Data Set** remaining after further screening out samples for which field notes indicate the presence of indoor (background) sources of VOCs, indoor air concentrations are significantly greater than the corresponding subsurface concentration, or attenuation factors for an individual chemical are inconsistent with the attenuation factors for other chemicals reported for the same pair of samples. The resulting data are also referred to as the **Baseline Screens Data Set** in the remainder of this document.

Indoor Air Screen (IA > Bkgd): Subset of **Baseline Screens Data Set** remaining after further screening out indoor air concentrations less than the “background” levels or less than the reporting limits (if RL is greater). The rationale for using the “background” levels is described in Section 4.4.

Source Strength Screens (GW > 100X Bkgd, GW > 500X Bkgd, GW > 1,000X Bkgd, GW > 5,000X Bkgd): Subsets of the Baseline Screens Data Set remaining after further screening out groundwater vapor concentrations less than certain multipliers (100, 500, 1,000, and 5,000) of “background” levels.

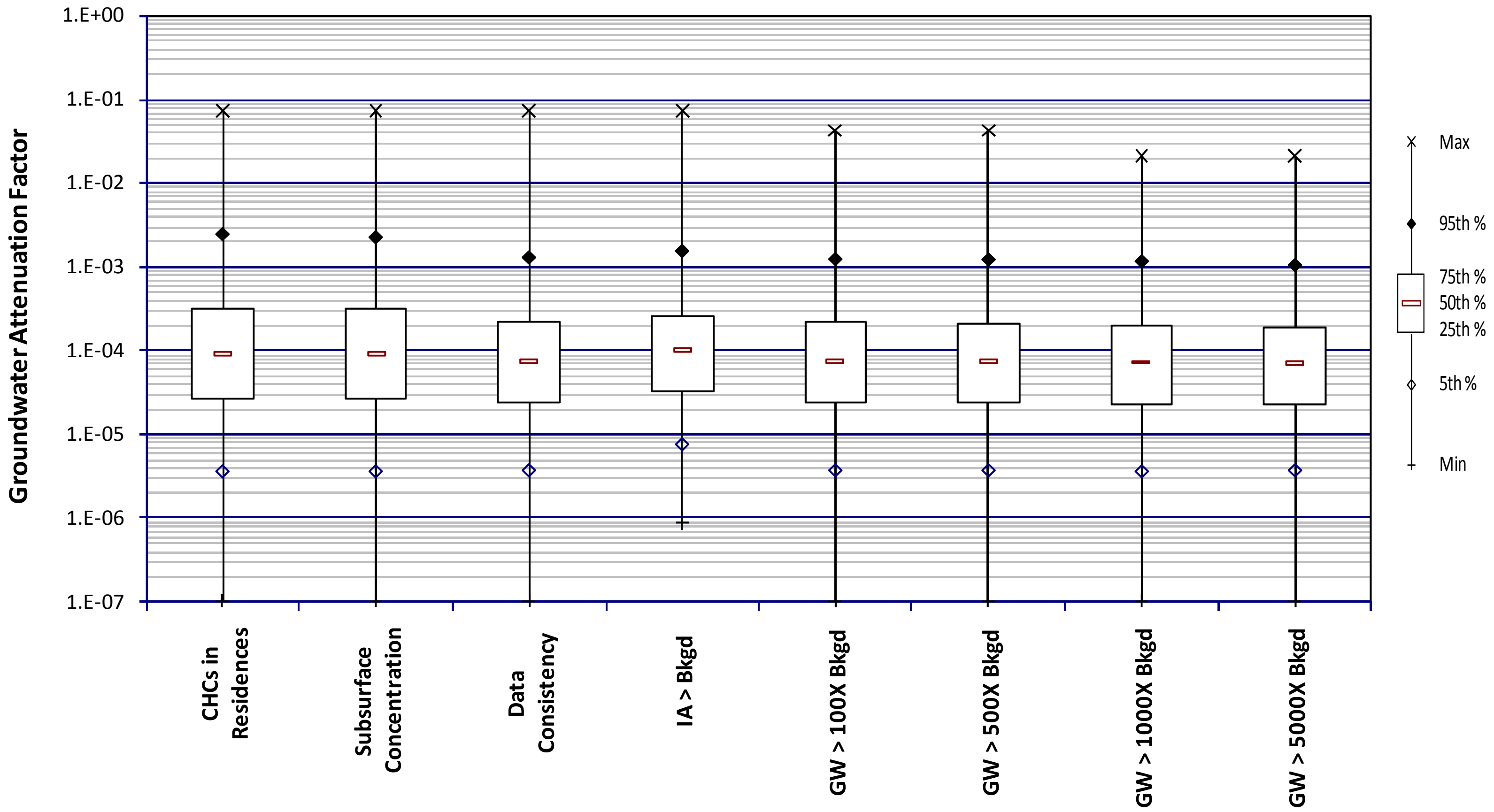


Figure 13. **Box-and-whisker plots summarizing groundwater attenuation factor distributions after application of various database screens.**

(Data sets and screens are summarized in footnotes to Table 7 and described in Sections 4.1 through 4.4.)

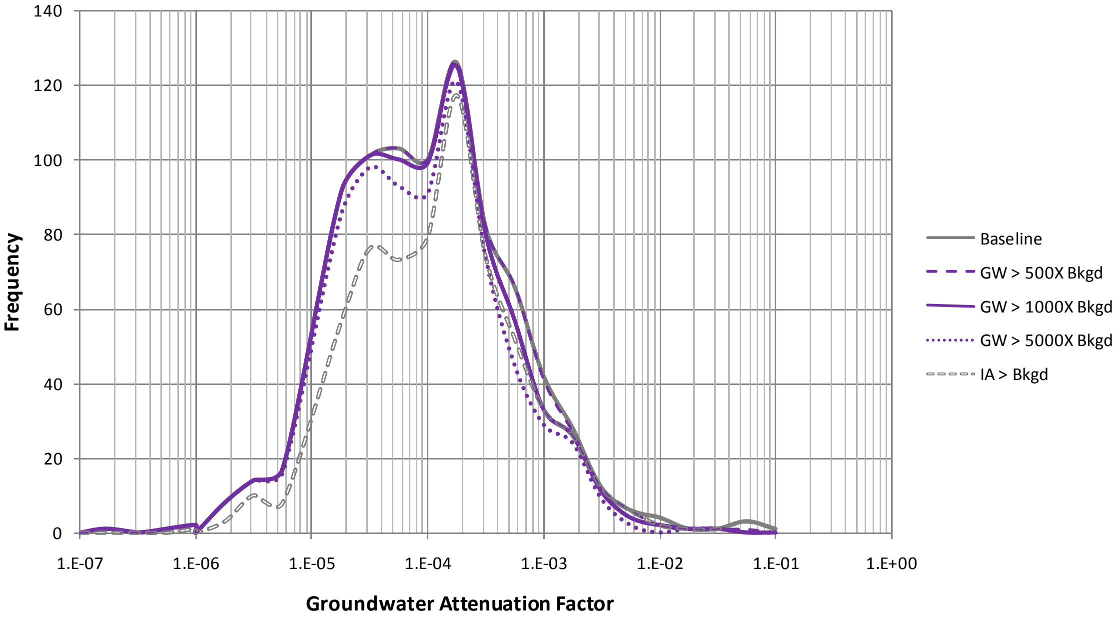


Figure 14. Frequency plots summarizing groundwater attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 7 and described in Sections 4.1 through 4.4.)

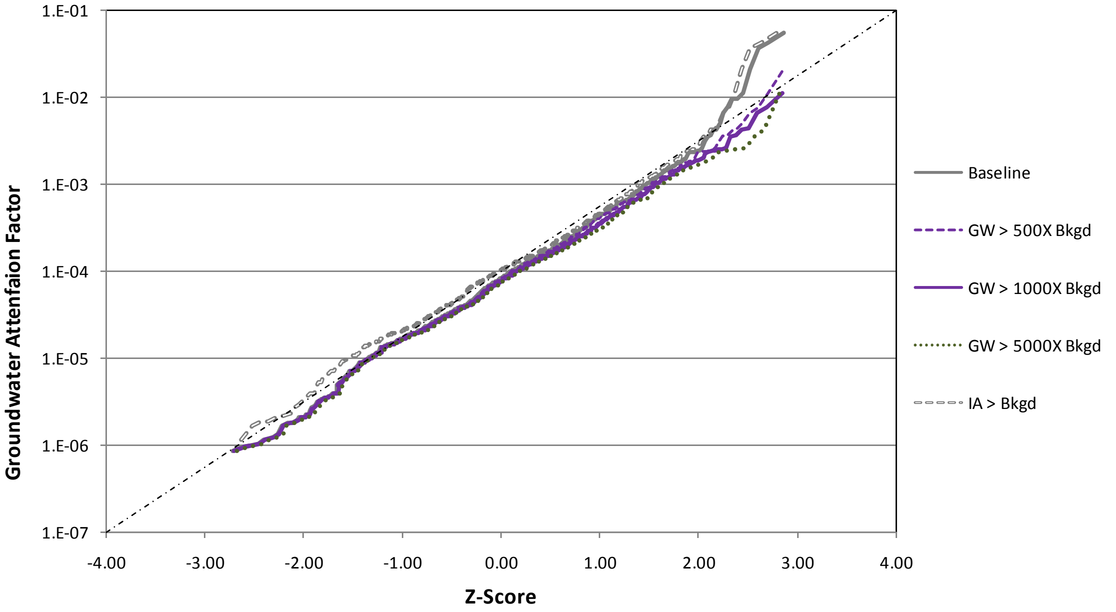
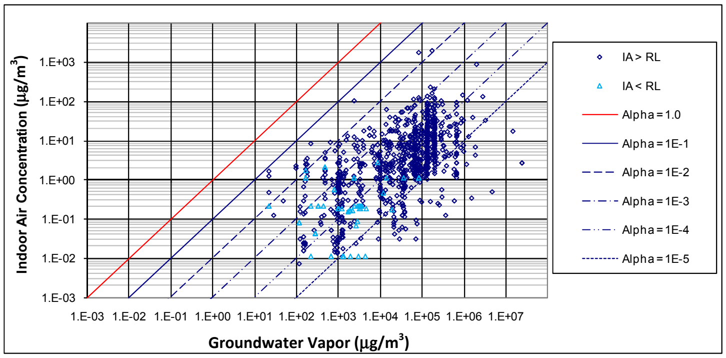


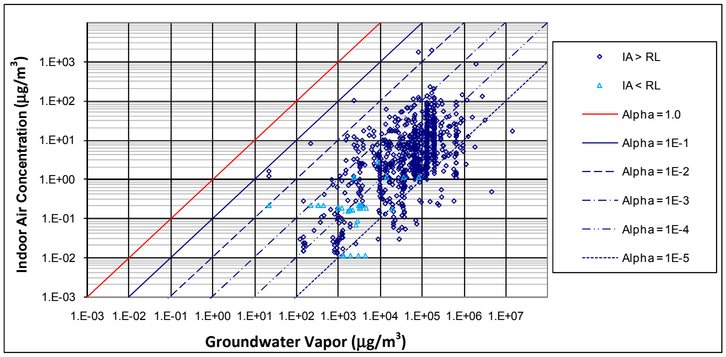
Figure 15. Cumulative probability plots summarizing groundwater attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 7 and described in Sections 4.1 through 4.4.)

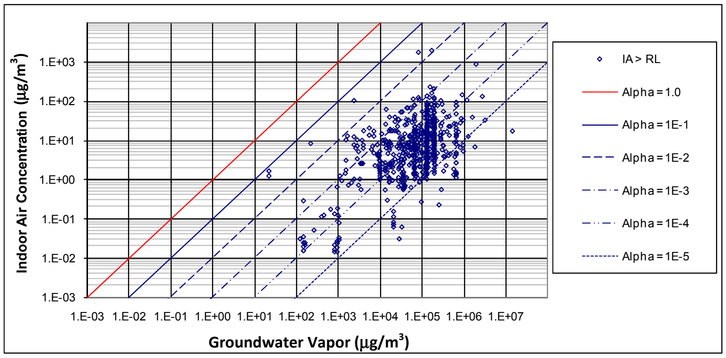
a) CHCs in Residences Data Set:



b) Baseline Data Set:



c) Indoor Air Screen Data Set
(IA > Bkgd):



d) Source Strength Screen Data Set
(GW > 1000X Bkgd):

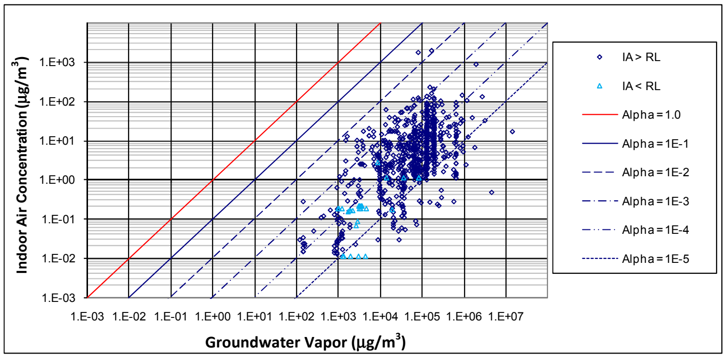


Figure 16. Scatter plots of paired indoor air and groundwater (vapor) concentrations for CHCs and residential buildings in EPA's vapor intrusion database after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 7 and described in Sections 4.1 through 4.4.)

4.5.3 Exterior Soil Gas Data

The descriptive statistics and box-and-whisker plots generated for the exterior soil gas attenuation factors and the screening criteria described above are shown in **Table 8** and **Figure 17**, respectively. Several multipliers of "background" were used to screen the indoor air or exterior soil gas concentrations in the **Baseline Screens Data Set**. Frequency plots and cumulative probability plots illustrating the distributions resulting from applying the screening criteria are shown in **Figures 18** and **19**, respectively. The corresponding scatter plots are shown in **Figure 20**.

Applying similar reasoning as for the subslab soil gas data, a **Source Strength Screen** with a multiplier of 50 times "background" (see solid line marked SG > 50X Bkgd) is the best screening criterion for minimizing the influence of background sources on the data set of exterior soil gas attenuation factors. This **Source Strength Screen** also has the advantage of retaining a greater number of attenuation factors than does the **Indoor Air Screen**. The source-strength screening criterion of 50 times "background" is used in the remainder of this report to further evaluate the exterior soil gas attenuation factors, as discussed in Section 5.0.

Table 8. Descriptive statistics of exterior soil gas attenuation factor distributions after application of various database screens.

	Applied Database Screen						
Statistic	**CHCs in Residences**	**Subsurface Concentration**	**Data Consistency**	**IA > Bkgd**	**SG > 50X Bkgd**	**SG > 100X Bkgd**	**SG > 500X Bkgd**
Min	5.0E-06	5.0E-06	5.0E-06	1.2E-05	5.0E-06	5.0E-06	5.0E-06
5%	9.4E-05	1.1E-04	9.4E-05	5.4E-04	7.6E-05	6.8E-05	6.0E-05
25%	2.1E-03	2.2E-03	2.1E-03	3.2E-03	6.0E-04	5.2E-04	3.1E-04
50%	1.6E-02	1.6E-02	1.6E-02	2.4E-02	3.8E-03	2.5E-03	1.5E-03
75%	8.2E-02	8.7E-02	8.4E-02	1.0E-01	2.7E-02	1.6E-02	6.7E-03
95%	6.0E-01	6.0E-01	3.6E-01	6.0E-01	2.5E-01	2.5E-01	9.7E-02
Max	1.9E+02	1.9E+02	3.5E+00	3.5E+00	1.3E+00	1.3E+00	1.1E+00
Mean	1.1E+00	1.1E+00	1.0E-01	1.4E-01	5.0E-02	5.0E-02	3.4E-02
StdDev	1.3E+01	1.4E+01	3.1E-01	4.2E-01	1.7E-01	1.8E-01	1.5E-01
95UCL	2.6E+00	2.7E+00	1.4E-01	2.1E-01	7.8E-02	8.1E-02	6.4E-02
Count All	213	202	176	89	106	94	67
Count >RL	202	202	176	89	106	94	67
Count <RL	11	0	0	0	0	0	0
No. of sites	13	13	13	10	11	10	10

CHCs in Residences Screen: Subset of database remaining after screening chemicals other than CHCs measured in residential settings.

Subsurface Concentration Screen: Subset of **CHCs in Residences Data Set** remaining after further screening out subsurface concentrations less than RLs.

Data Consistency Screen: Subset of **Subsurface Concentration Screen Data Set** remaining after further screening out samples for which field notes indicate the presence of indoor (background) sources of VOCs, indoor air concentrations are significantly greater than the corresponding subsurface concentration, or attenuation factors for an individual chemical are inconsistent with the attenuation factors for other chemicals reported for the same pair of samples. The resulting data are also referred to as the **Baseline Screens Data Set** in the remainder of this document.

Indoor Air Screen (IA > Bkgd): Subset of **Baseline Screens Data Set** remaining after further screening out indoor air concentrations less than the "background" levels or less than the RLs (if RL is greater than the 90th percentile). The rationale for using the "background" levels is described in Section 4.4.

Source Strength Screens (SG > 50X Bkgd, SG > 100X Bkgd, SG > 500X Bkgd): Subsets of the **Baseline Screens Data Set** remaining after further screening out exterior soil gas concentrations less than certain multipliers (50, 100, and 500) of "background" levels.

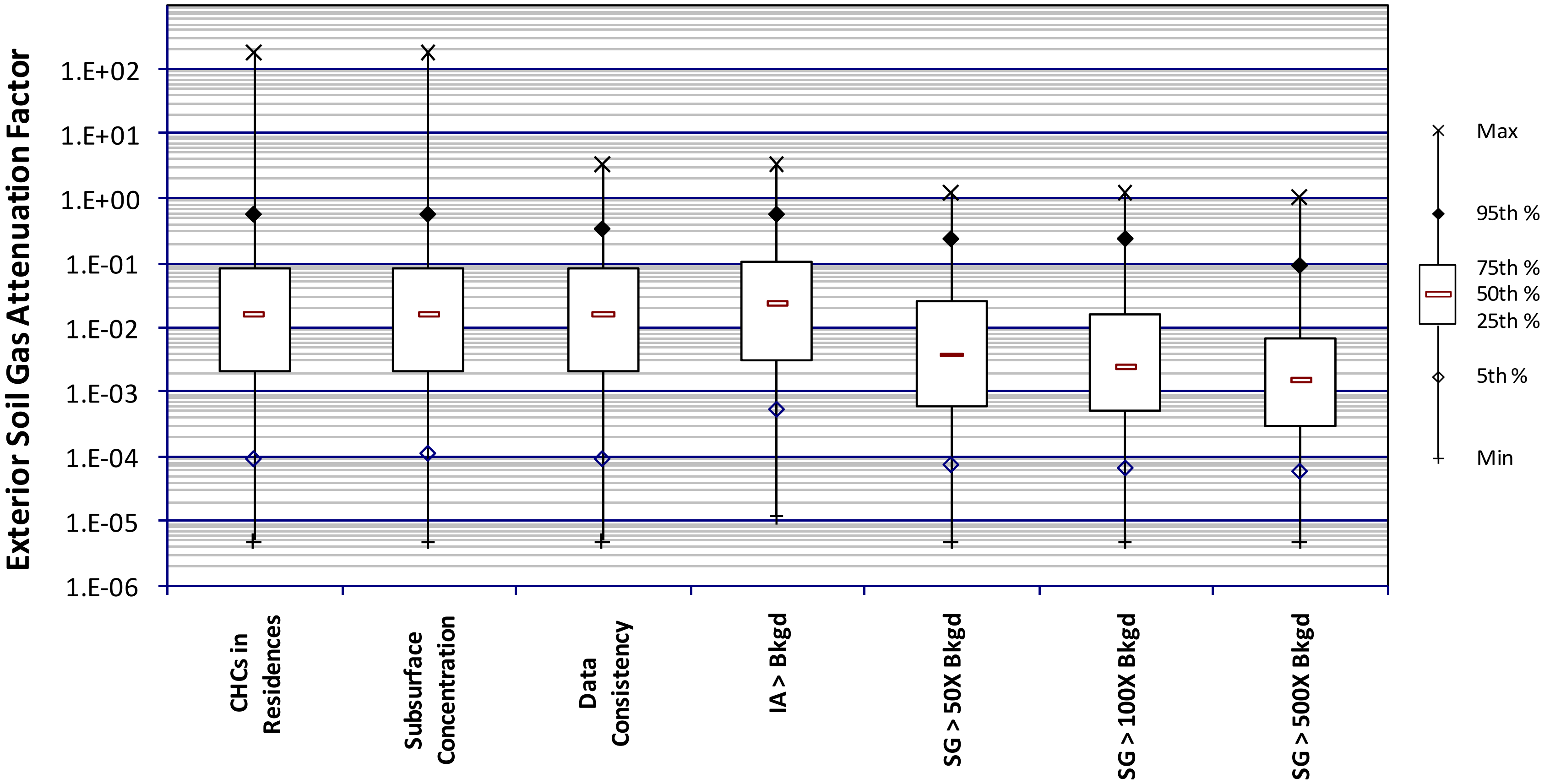


Figure 17. **Box-and-whisker plots summarizing exterior soil gas attenuation factor distributions after application of various database screens.**

(Data sets and screens are summarized in footnotes to Table 8 and described in Sections 4.1 through 4.4.)

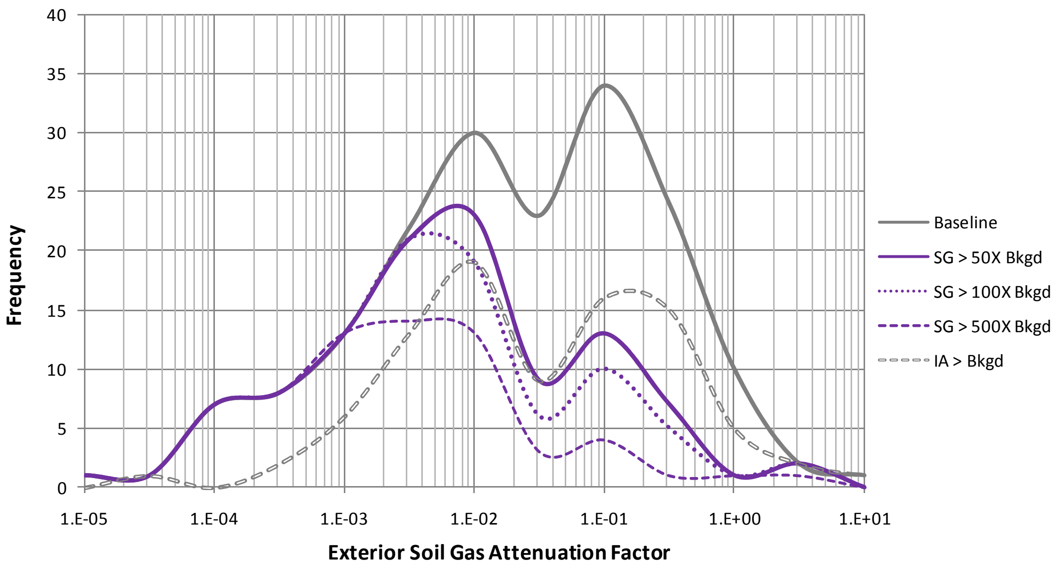


Figure 18. Frequency plots summarizing exterior soil gas attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 8 and described in Sections 4.1 through 4.4.)

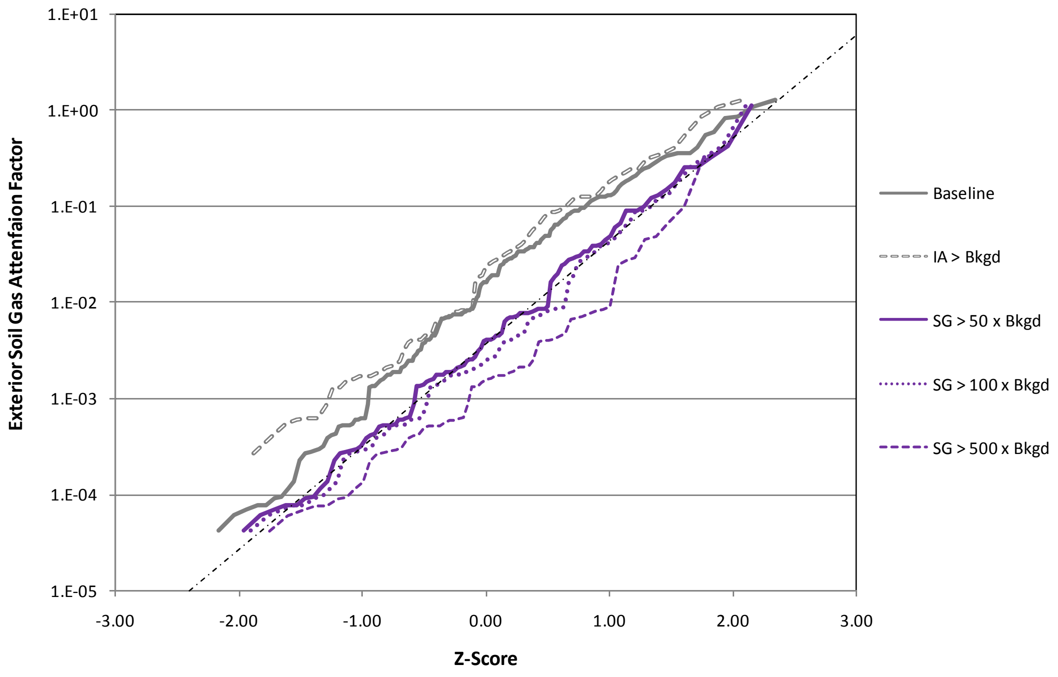
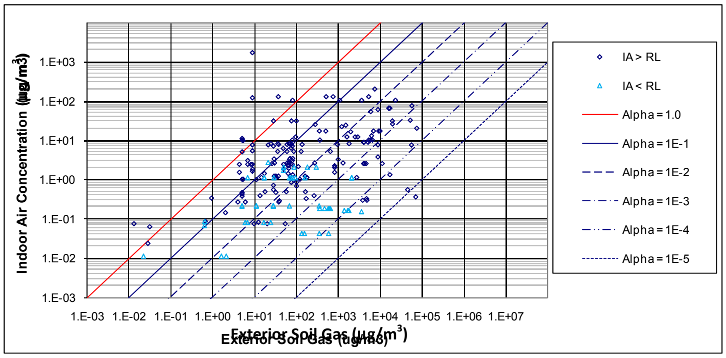


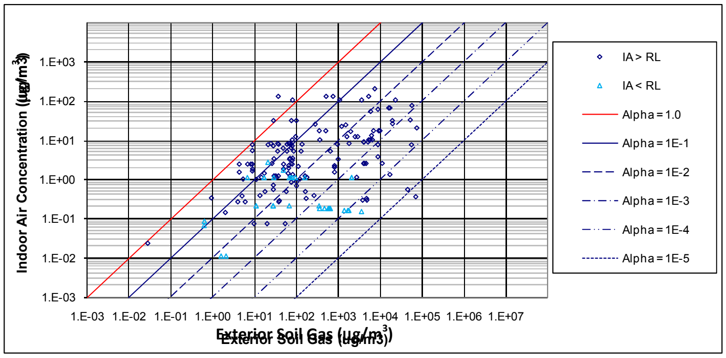
Figure 19. Cumulative probability plots summarizing exterior soil gas attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 8 and described in Sections 4.1 through 4.4.)

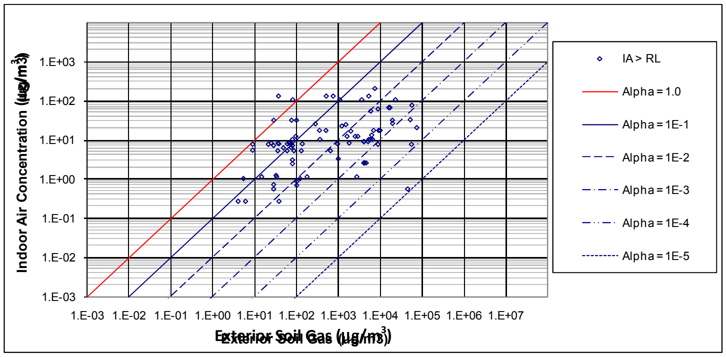
a) CHCs in Residences Data Set:



b) Baseline Data Set:



c) Indoor Air Screen Data Set
(IA > Bkgd):



d) Source Strength Screen Data Set
(SG > 50X Bkgd):

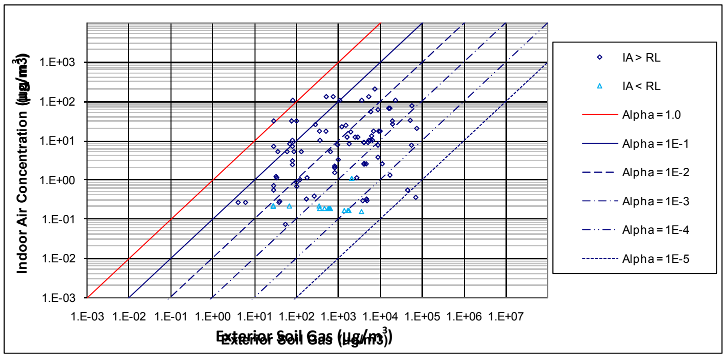


Figure 20. Scatter plots of paired indoor air and exterior soil gas concentrations for CHCs and residential buildings in EPA's vapor intrusion database after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 8 and described in Sections 4.1 through 4.4.)

4.5.4 Crawlspace Data

The descriptive statistics and box-and-whisker plots generated for the crawlspace attenuation factors and the screening criteria described above are shown in **Table 9** and **Figure 21**, respectively. Several multipliers of "background" were used to screen the **Baseline Screens Data Set**. Frequency plots and cumulative probability plots illustrating the distributions resulting from applying the screening criteria are shown in **Figures 22** and **23**, respectively. The corresponding scatter plots are shown in **Figure 24**.

Table 9. Descriptive statistics of crawlspace attenuation factor distributions after application of various database screens.

	Applied Database Screen						
Statistic	**CHCs in Residences**	**Subsurface Concentration**	**Data Consistency**	**IA > Bkgd**	**CS > Bkgd**	**CS > 5X Bkgd**	**CS > 10X Bkgd**
Min	3.2E-02	3.2E-02	3.2E-02	5.7E-02	3.2E-02	3.2E-02	3.2E-02
5%	6.5E-02	6.5E-02	3.3E-02	1.0E-01	3.3E-02	3.3E-02	3.3E-02
25%	2.9E-01	2.9E-01	1.8E-01	2.2E-01	1.8E-01	1.8E-01	1.8E-01
50%	6.6E-01	6.6E-01	3.7E-01	3.9E-01	3.5E-01	3.5E-01	3.5E-01
75%	1.1E+00	1.1E+00	6.1E-01	6.9E-01	6.1E-01	6.1E-01	5.5E-01
95%	4.1E+00	4.0E+00	9.2E-01	9.0E-01	9.0E-01	9.0E-01	9.0E-01
Max	1.0E+01	8.5E+00	1.0E+00	9.2E-01	9.2E-01	9.2E-01	9.2E-01
Mean	1.2E+00	1.1E+00	4.3E-01	4.6E-01	4.3E-01	4.1E-01	3.9E-01
StdDev	1.7E+00	1.5E+00	2.9E-01	2.8E-01	2.9E-01	2.9E-01	2.7E-01
95UCL	1.5E+00	1.3E+00	4.9E-01	5.3E-01	5.0E-01	4.9E-01	4.7E-01
Count All	91	90	51	41	45	39	33
Count >RL	91	90	51	41	45	39	33
Count <RL	0	0	0	0	0	0	0
No. of sites	4	4	4	4	4	3	3

CHCs in Residences Screen: Subset of database remaining after screening chemicals other than CHCs measured in residential settings.

Subsurface Concentration Screen: Subset of **CHCs in Residences Data Set** remaining after further screening out subsurface concentrations less than RLs.

Data Consistency Screen: Subset of **Subsurface Concentration Screen Data Set** remaining after further screening out samples for which field notes indicate the presence of indoor (background) sources of VOCs, indoor air concentrations are significantly greater than the corresponding subsurface concentration, or attenuation factors for an individual chemical are inconsistent with the attenuation factors for other chemicals reported for the same pair of samples. The resulting data are also referred to as the **Baseline Screens Data Set** in the remainder of this document.

Indoor Air Screen (IA > Bkgd): Subset of **Baseline Screens Data Set** remaining after further screening out indoor air concentrations less than the "background" levels or less than the RLs (if RL is greater). The rationale for using the "background" levels is described in Section 4.4.

Source Strength Screens (CS > Bkgd, CS > 5X Bkgd, CS > 10X Bkgd): Subsets of the **Baseline Screens Data Set** remaining after further screening out crawlspace concentrations less than certain multipliers (1, 5, and 10) of "background" levels.

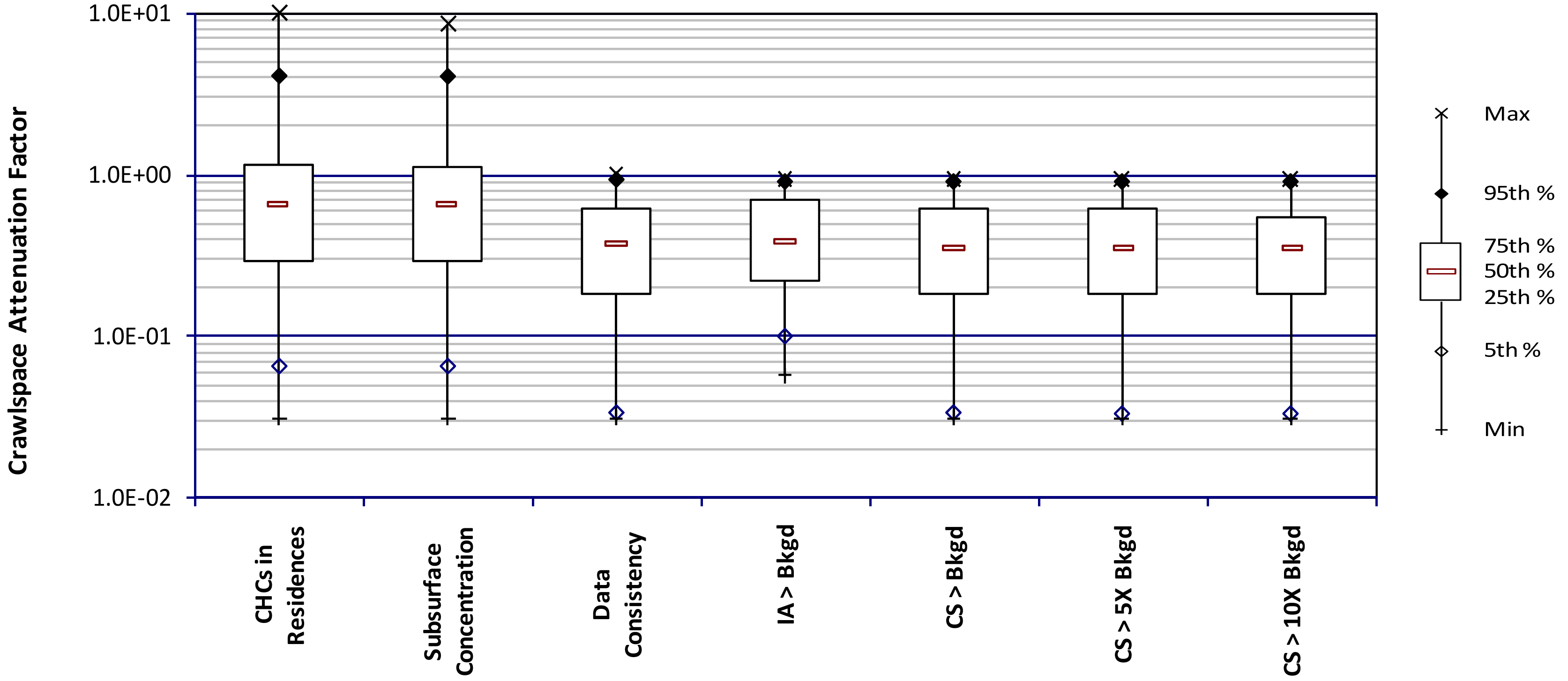


Figure 21. Box-and-whisker plots summarizing crawlspace attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 9 and described in Sections 4.1 through 4.4.)

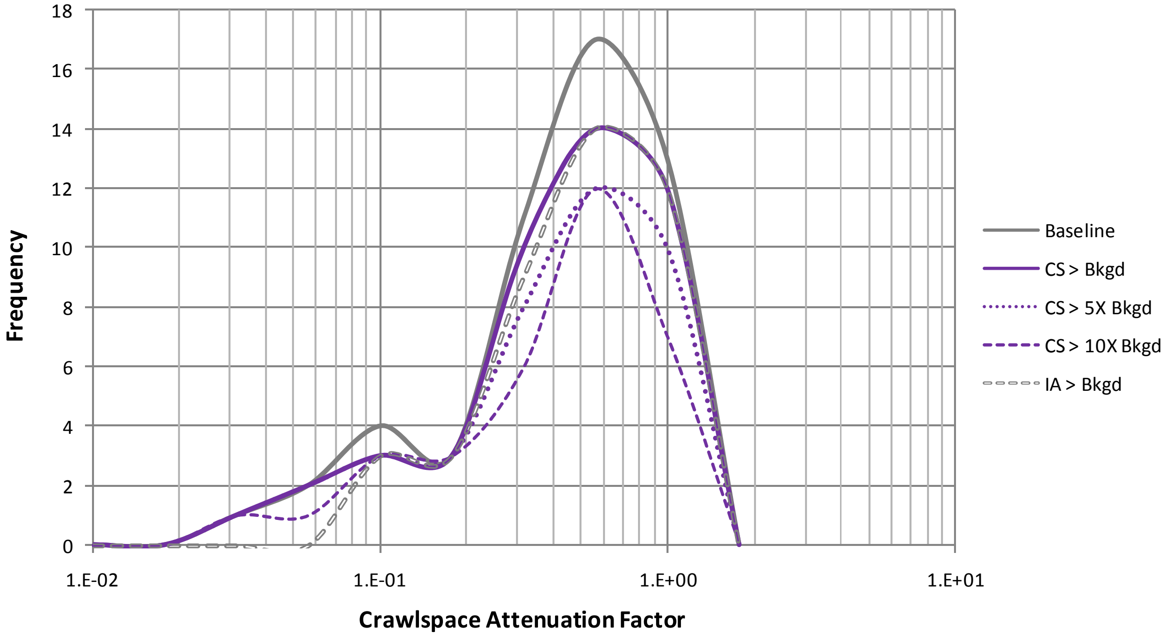


Figure 22. Frequency plots summarizing crawlspace attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 9 and described in Sections 4.1 through 4.4.)

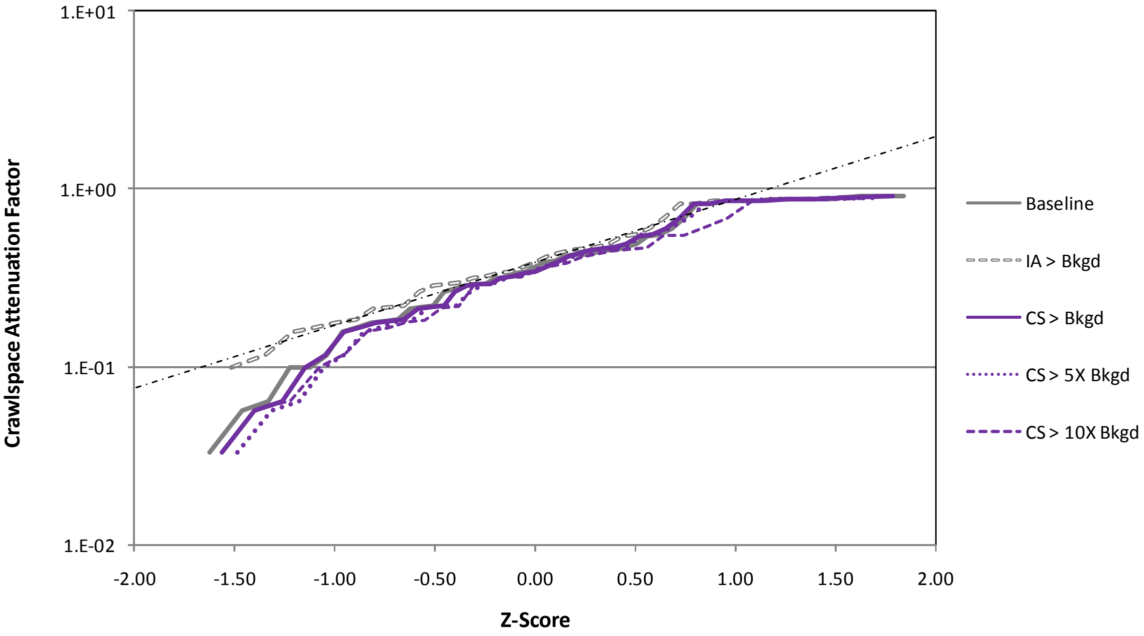
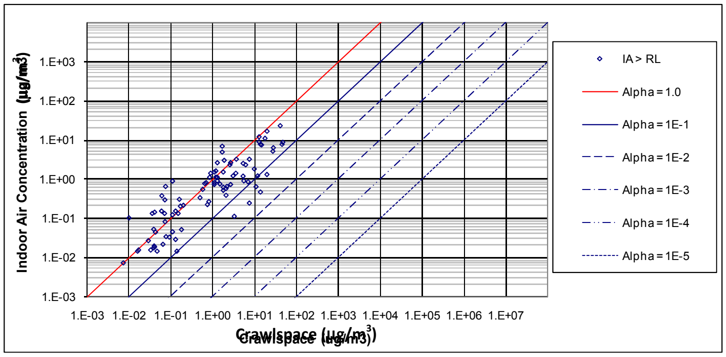


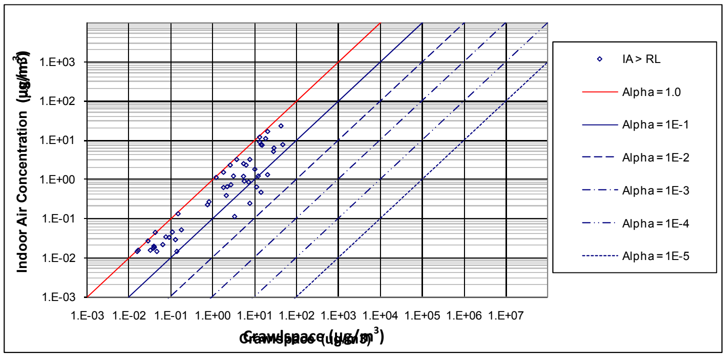
Figure 23. Cumulative probability plots summarizing crawlspace attenuation factor distributions after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 9 and described in Sections 4.1 through 4.4.)

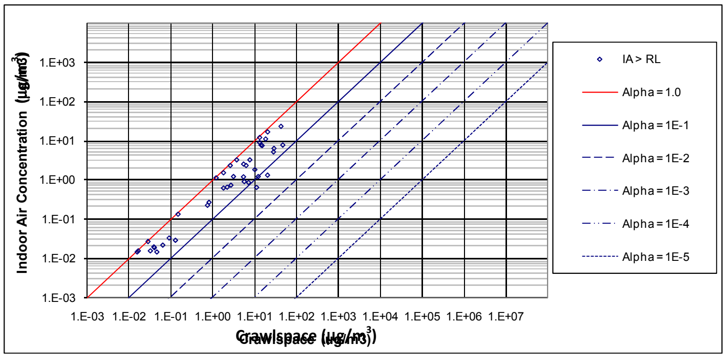
a) CHCs in Residences Data Set:



b) Baseline Data Set:



c) Indoor Air Screen Data Set
(IA > Bkgd):



d) Source Strength Screen Data Set
(CS > Bkgd):

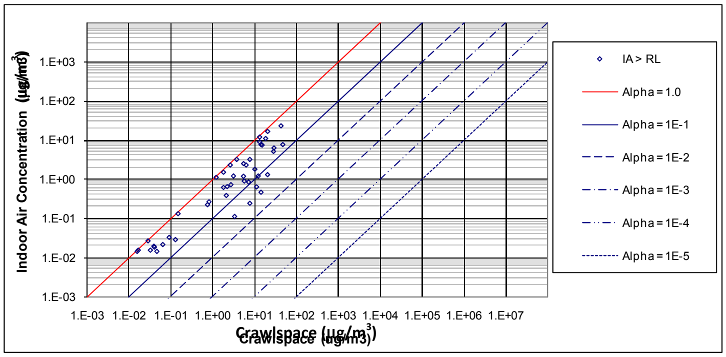


Figure 24. Scatter plots of paired indoor air and crawlspace concentrations for CHCs and residential buildings in EPA's vapor intrusion database after application of various database screens.

(Data sets and screens are summarized in footnotes to Table 9 and described in Sections 4.1 through 4.4.)

Applying similar reasoning as for the subslab soil gas data (i.e., selecting the screening criteria that results in frequency plots most closely appearing "normal" and cumulative probability plots most closely approaching linearity), the **Indoor Air Screen**, which screens out indoor air concentrations less than "background" or less than the RLs, is selected as the best screening criterion for minimizing the influence of background sources on the data set of crawlspace attenuation factors (see dashed gray line marked IA > Bkgd). The **Indoor Air Screen** is used in the remainder of this report to further evaluate the crawlspace attenuation factors, as discussed in Section 5.0.

The screening criteria used for crawlspace attenuation factors as a result of this analysis differ from the screening criteria selected for the other media. This result may reflect the greater likelihood of air exchange occurring between indoor spaces and crawlspaces than would be expected between indoor spaces and soil gas underlying a slab or basement.

5.0 Discussion of Findings

The data contained in EPA's vapor intrusion database were compiled to help understand the vapor intrusion pathway and particularly the attenuation in VOC concentrations that may be observed when vapors migrate from subsurface sources and enter indoor spaces. As described in Section 4.0, EPA screened the database using certain criteria to identify and remove data likely to be influenced by background sources, leaving a subset of attenuation factors for CHCs in residential settings that are considered representative of vapor intrusion processes.

Section 5.0 discusses and compares the distributions and descriptive statistics for the resulting subset of attenuation factors for each source medium (subslab soil gas, groundwater, exterior soil gas, and crawlspace soil gas). Each of these vapor intrusion pathway attenuation factors is analyzed to illustrate and evaluate the attenuation factor distributions for individual sites. In addition, the subslab soil gas and groundwater attenuation factors were evaluated for individual chemicals, the subslab soil gas attenuation factors were evaluated for different building characteristics (e.g., foundation type), and the groundwater attenuation factors were evaluated for the influence of general soil type and depth to groundwater.

EPA's vapor intrusion database presents the most comprehensive compilation of vapor intrusion data for chlorinated hydrocarbons in residences available at this time. The observations summarized here based on empirical attenuation factor distributions are considered representative of vapor intrusion of CHCs from subsurface sources into buildings for most conditions. Nevertheless, it is important to consider that the database represents only a subset of the hundreds of vapor intrusion sites nationwide and may not apply to new sites with significantly different subsurface or building conditions.

5.1 Subslab Soil Gas-to-Indoor-Air Attenuation Factors

Empirical subslab soil gas attenuation factors are calculated by dividing an indoor air concentration (C_{IA}) measured in a building by the vapor concentration measured directly underneath the foundation slab of the same building (C_{SS}) (i.e., Equation 3 with the subslab soil gas concentration [C_{SS}] as the source concentration [C_{SV}]). As indicated by Equations 4a and 4b, the empirical subslab soil gas attenuation factor is expected to be influenced solely by building characteristics, including potential indoor sources of VOCs, and is synonymous with $AF_{EMP,bldg}$. It is not expected to depend on soil characteristics that influence attenuation through the vadose zone (AF_{soil}).

Table 10 provides selected statistics and **Figure 25** shows box-and-whisker plots for individual sites compared with the statistics for the combined screened subslab soil gas attenuation factors. For the combined subslab soil gas data set (i.e., all sites, all CHCs), at a source-strength filter level of 50 times "background," the median subslab soil gas attenuation factor is approximately 3E-03 (0.003), and the 95th percentile value is approximately 3E-02 (0.03) (both rounded to one significant figure). These empirical subslab soil gas attenuation factors are supported by theoretical calculations, as follows:

- A mass balance analysis, assuming a well-mixed interior volume and steady-state conditions, indicates that the theoretical (true) subslab soil gas attenuation factor (AF_{Bldg}) can be expressed as the ratio of the soil gas entry rate (Q_{soil}) to the building ventilation rate (Q_{Bldg}) (Song et al., 2011) for cases where there is no background contribution to the indoor air concentration.

  $$AF_{Bldg} = \frac{C_{IA}}{C_{SS}} = \frac{Q_{soil}}{Q_{Bldg}} \qquad \text{Equation 6a}$$

  For cases where there are background source contributions to the indoor air concentration, the empirical (or apparent) subslab soil gas attenuation factor (AF_{Bldg}) is not simply expressed as the ratio of the soil gas entry rate (Q_{soil}) to the building ventilation rate (Q_{Bldg}).

  $$AF_{EMP,Bldg} = \frac{C_{IA}}{C_{SS}} = \frac{Q_{soil}}{Q_{Bldg}} + \frac{C_{IA-BKGD}}{C_{SS}} \qquad \text{Equation 6b}$$

  All symbols are as defined previously.

- Because the empirical subslab soil gas attenuation factors have been screened to minimize the influence of background sources on indoor air concentrations, Equation 6a is more applicable for deriving theoretical "true" attenuation factors to compare with the empirically derived attenuation factors.
- Using median values for residential building volume and air exchange rates (395 m^3 and 0.45 air changes per hour, respectively) provided in the *Exposure Factors Handbook 2011 Edition* (EPA, 2011b) and a central value of 5 L/min for Q_{soil} in sandy materials (EPA 2002, Appendix G), the median value of the subslab soil gas attenuation factor (according to Equation 6a), is expected to be approximately 0.002. Using upper-end (10th percentile) values for residential building volume and air exchange rates (154 m^3 and 0.18 air changes per hour, respectively (EPA, 2011b) and Q_{soil} (10 L/min), an upper-end value of 0.02 for the subslab soil gas attenuation factor is obtained.
- These theoretical values (0.002 and 0.02, respectively) are very close to the observed empirical median and 95th percentile values obtained with the **Source Strength Screen** using a multiplier of 50 times "background" (0.003 and 0.03, respectively).

Table 10. Descriptive statistics summarizing subslab soil gas attenuation factor distributions for individual sites after Source Strength Screen (subslab soil gas concentrations > 50 times "background").

Statistic	SS > 50X Bkgd	BillingsPCE	DenverPCEBB	Endicott	Georgetown	Harcros/Tri State	Hopewell Precision	Jackson	LAFB	Orion Park	Raymark	SCM-Cortlandville	West Side Corporation
Min	2.5E-05	2.5E-05	1.1E-03	2.6E-04	1.3E-03	3.8E-04	1.5E-03		3.5E-05	5.0E-04	2.5E-04	3.4E-03	2.0E-04
5%	3.2E-04	9.6E-05		6.9E-04			1.9E-03		1.4E-04		1.2E-03	3.6E-03	
25%	1.5E-03	4.6E-04		1.7E-03			5.0E-03		4.1E-04	1.8E-03	2.0E-03	7.1E-03	5.9E-04
50%	2.7E-03	7.0E-04	6.4E-03	2.6E-03	1.9E-03	4.5E-04	1.0E-02	8.4E-03	1.9E-03	2.8E-03	5.5E-03	1.8E-02	1.5E-03
75%	6.8E-03	1.5E-03		5.0E-03			1.8E-02		5.3E-03	8.8E-03	8.3E-03	4.1E-02	9.7E-03
95%	2.6E-02	2.6E-03		1.1E-02			3.4E-02		3.2E-02		2.1E-02	1.5E-01	
Max	9.4E-01	2.7E-03	4.1E-02	9.4E-01	2.9E-03	2.7E-03	3.4E-02		4.2E-02	3.3E-02	7.9E-02	1.5E-01	3.5E-01
Mean	9.2E-03	9.5E-04	1.7E-02	8.5E-03	2.0E-03	1.0E-03	1.3E-02	8.4E-03	5.0E-03	7.6E-03	7.4E-03	4.1E-02	4.3E-02
StdDev	5.0E-02	7.7E-04	1.9E-02	6.5E-02	8.4E-04	1.1E-03	1.0E-02		9.0E-03	1.1E-02	1.0E-02	5.0E-02	1.2E-01
95UCL	1.3E-02	1.2E-03	3.5E-02	1.6E-02	3.5E-03	2.3E-03	1.7E-02		7.1E-03	1.4E-02	9.2E-03	6.8E-02	1.2E-01
No. of AFs	431	27	5	207	3	4	19	1	52	9	83	12	9
No. of AFs > RL	411	27	5	188	3	4	19	1	52	9	83	12	8
No. of AFs < RL	20	0	0	19	0	0	0	0	0	0	0	0	1

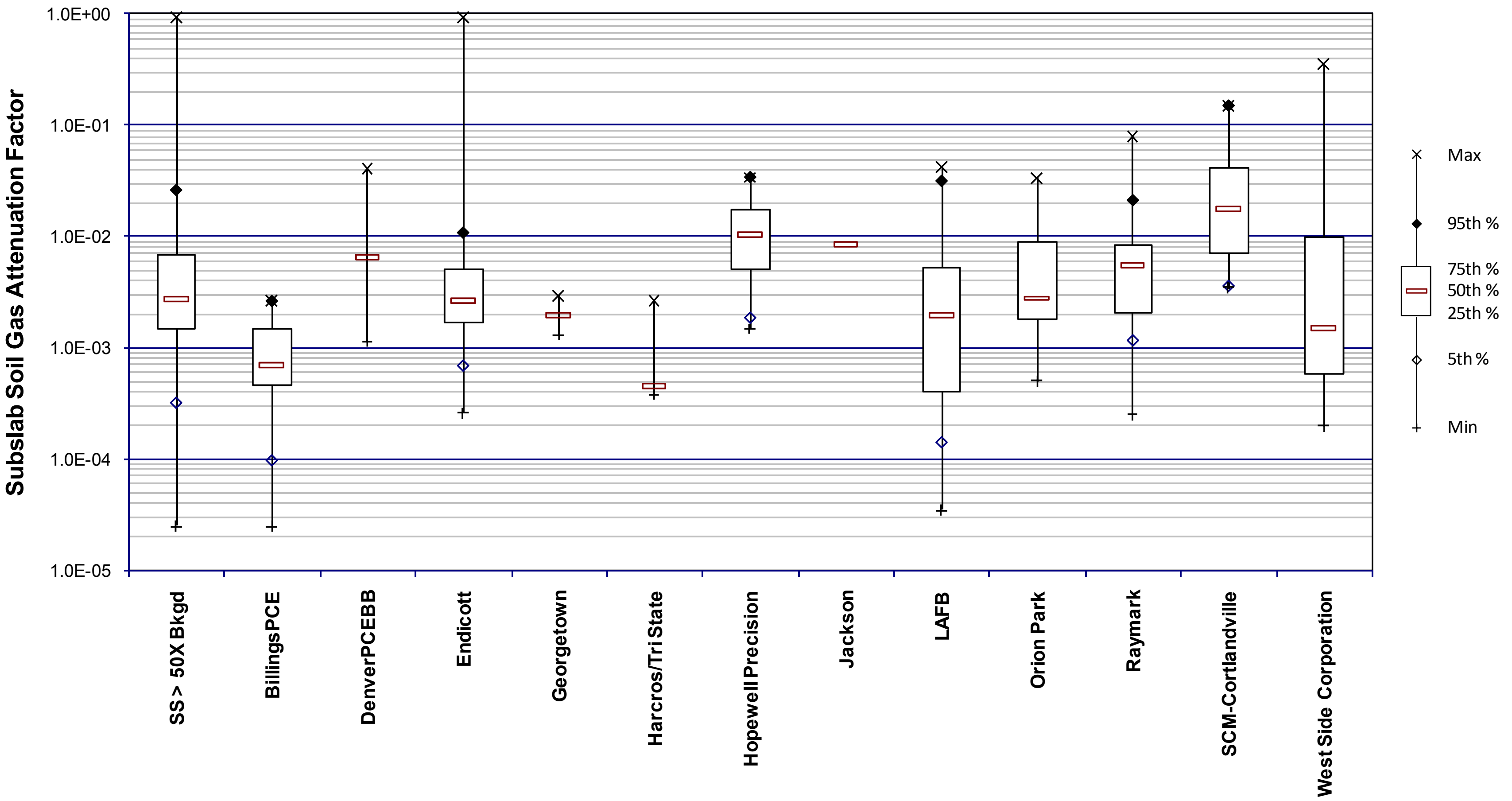


Figure 25. Box-and-whisker plots summarizing subslab soil gas attenuation factor distributions for individual sites after Source Strength Screen (subslab soil gas concentrations > 50 times "background").

Table 10 and **Figure 25** demonstrate intra-site variability in the subslab soil gas attenuation factor. The inter-quartile range (i.e., the range from the 25th to 75th percentile values) spans less than one order of magnitude total (i.e., between approximately 2E-03 and 7E-03, respectively) for the combined screened data set and for six of the eight sites for which these statistics could be calculated. The range from the 5th to 95th percentile values exceeds two orders of magnitude total for the combined screened data set and for four of the six sites for which these statistics could be calculated.

Table 10 and **Figure 25** also demonstrate inter-site variability in the subslab soil gas attenuation factor. The median subslab soil gas attenuation factors differ by more than one order of magnitude across the 12 sites (ranging from approximately 5E-04 to approximately 2E-02). The 95th percentile subslab soil gas attenuation factors differ by approximately two orders of magnitude across the six sites for which these statistics could be calculated (ranging from approximately 3E-03 to approximately 2E-01). All but one of the sites have 95th percentile values that are below 0.03, the value calculated for the combined data.

Table 11 and **Figure 26** show the subslab soil gas attenuation factors for two foundation types, compared with the combined set of data. The median, 25th percentile, 75th percentile, and 95th percentile values for residences with basements are similar to the respective statistic for residences with a slab-on-grade foundation. This may be interpreted to suggest that poured concrete foundations, whether in a basement or as a slab on grade, have similar vapor attenuation characteristics.

Table 12 and **Figure 27** show the subslab soil gas attenuation factors for the four most commonly encountered chlorinated hydrocarbons in the combined data set, each of which was a chemical of concern at four or more sites and with at least 28 values after screening. The median subslab soil gas attenuation factor for these four volatile chemicals fell within a range of approximately 2E-03 for PCE to approximately 4E-03 for 1,1,1,-trichloroethane. Likewise, the 95th percentile subslab soil gas attenuation factor for these four volatile chemicals fell within a range of approximately 1E-02 for 1,1,1,-trichloroethane to approximately 3E-02 for PCE and TCE. These observations are consistent with the conceptual model of vapor intrusion, which predicts that chemicals with similar fate-and-transport properties, such as CHCs, are expected to have similar attenuation factor values. The variability that is observed among these chemicals may be attributed to analytical uncertainty, particularly at concentrations near the RLs for these substances.

Table 11. Descriptive statistics summarizing subslab soil gas attenuation factor distributions for two foundation types after Source Strength Screen (subslab soil gas concentrations > 50 times "background").

		Foundation	
Statistic	**SS > 50X Bkgd**	**Basement**	**Slab-On-Grade**
Min	2.5E-05	2.5E-05	4.5E-04
5%	3.2E-04	3.1E-04	5.0E-04
25%	1.5E-03	1.5E-03	8.7E-04
50%	2.7E-03	2.8E-03	2.8E-03
75%	6.8E-03	7.1E-03	7.0E-03
95%	2.6E-02	2.9E-02	1.4E-02
Max	9.4E-01	9.4E-01	3.3E-02
Mean	9.2E-03	1.0E-02	5.3E-03
StdDev	5.0E-02	5.3E-02	7.6E-03
95UCL	1.3E-02	1.4E-02	8.2E-03
No. of AFs	431	377	20
No. of AFs > RL	411	365	18
No. of AFs < RL	20	12	2
No. of sites	12	9	3

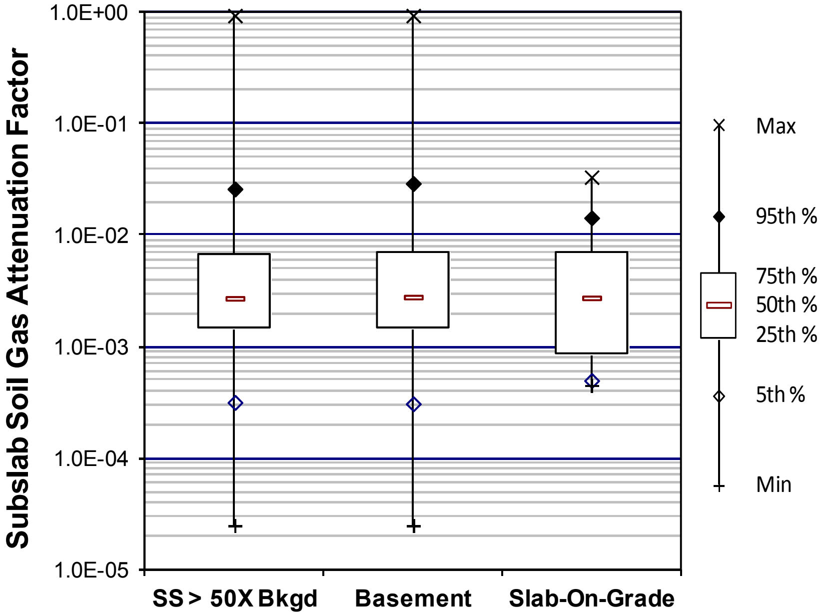


Figure 26. Box-and-whisker plots summarizing subslab soil gas attenuation factor distributions for two foundation types after Source Strength Screen (subslab soil gas concentrations > 50 times "background").

Table 12. Descriptive statistics summarizing subslab soil gas attenuation factor distributions for specific VOCs after Source Strength Screen (subslab soil gas concentrations > 50 times "background").

Abbreviations: TCE = trichloroethylene; PCE = tetrachloroethylene; 111TCA = 1,1,1-trichloroethane; and 11DCE = 1,1-dichloroethylene.

		Chemical			
Statistic	**SS > 50X Bkgd**	**TCE**	**PCE**	**111TCA**	**11DCE**
Min	2.5E-05	3.5E-05	2.5E-05	2.6E-04	1.6E-04
5%	3.2E-04	3.1E-04	2.0E-04	1.1E-03	2.5E-04
25%	1.5E-03	1.6E-03	6.4E-04	2.0E-03	9.2E-04
50%	2.7E-03	2.8E-03	1.5E-03	3.6E-03	2.4E-03
75%	6.8E-03	6.8E-03	3.0E-03	7.0E-03	7.7E-03
95%	2.6E-02	3.2E-02	3.2E-02	1.3E-02	1.8E-02
Max	9.4E-01	1.5E-01	3.5E-01	7.9E-02	1.9E-02
Mean	9.2E-03	7.4E-03	8.6E-03	6.1E-03	4.7E-03
StdDev	5.0E-02	1.6E-02	4.2E-02	1.0E-02	5.0E-03
95UCL	1.3E-02	9.4E-03	1.7E-02	8.1E-03	6.3E-03
No. of AFs	431	194	71	70	28
No. of AFs > RL	411	187	70	70	28
No. of AFs < RL	20	7	1	0	0
No. of sites	12	6	7	4	4

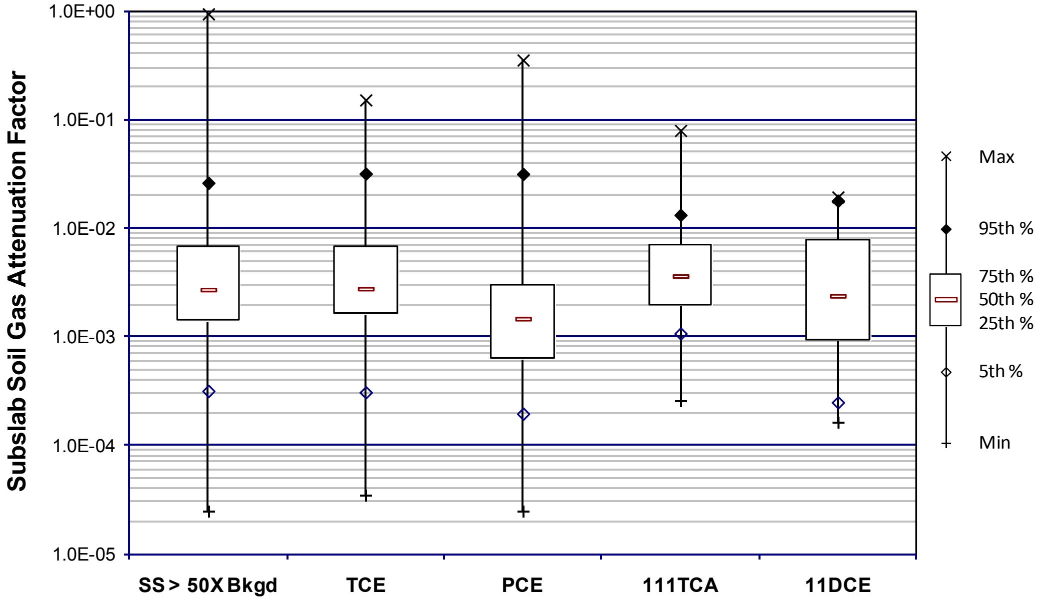


Figure 27. Box-and-whisker plots summarizing subslab soil gas attenuation factor distributions for specific VOCs after Source Strength Screen (subslab soil gas concentrations > 50 times "background").

Abbreviations: TCE = trichloroethylene; PCE = tetrachloroethylene; 111TCA = 1,1,1-trichloroethane; and 11DCE = 1,1-dichloroethylene.

5.2 Groundwater-to-Indoor-Air Attenuation Factors

Empirical groundwater attenuation factors are calculated by dividing an indoor air concentration measured in a building (C_{IA}) by the vapor concentration corresponding to the groundwater concentration underlying or near the building (i.e., Equation 3 with the groundwater vapor concentration as the source concentration [C_{SV}]). The groundwater's vapor concentration is estimated by multiplying the groundwater concentration by a chemical's dimensionless Henry's law constant at the groundwater temperature appropriate for the site. The equations and chemical properties used to convert groundwater concentrations to vapor concentrations at *in-situ* groundwater temperatures are provided in **Appendix D.**

Table 13 provides selected statistics, and **Figure 28** shows box-and-whisker plots for individual sites compared with the statistics for the combined set of screened groundwater attenuation factors. For the combined groundwater data set (i.e., all sites, all CHCs), at a source-screen filter level of 1,000 times "background," the median groundwater attenuation factor is approximately 7E-05 (0.00007), the inter-quartile range (i.e., the range from the 25th to 75th percentile values) spans approximately one order of magnitude (i.e., between approximately 2E-05 and 2E-04, respectively), and the 5th to 95th percentile spans almost three orders of magnitude (i.e., ranging from 4E-06 to 1E-03). These values are at least an order of magnitude smaller than the equivalent statistics for the combined set of subslab soil gas attenuation factors (indicating more reduction in vapor concentrations during vapor migration from groundwater sources and entry into residences), which is consistent with the conceptual model for vapor intrusion and the definition of these two terms. As indicated by Equations 4a and 4b, the empirical groundwater attenuation factors are expected to be influenced by soil characteristics that influence attenuation in the vadose zone (AF_{soil}), in addition to building characteristics ($AF_{EMP,bldg}$), whereas the subslab soil gas attenuation factors are expected to be influenced primarily only by building characteristics.

Table 13 and **Figure 28** demonstrate intra-site variability in the groundwater attenuation factor. The inter-quartile range spans more than one order of magnitude for seven of the 13 sites for which these statistics could be calculated. The range from the 5th to 95th percentile values exceeds two orders of magnitude for 6 of the 13 sites for which these statistics could be calculated. **Table 13** and **Figure 28** also demonstrate inter-site variability in the groundwater attenuation factor. The median groundwater attenuation factor varies by more than two orders of magnitude across the 24 sites (ranging from approximately 3E-06 to approximately 6E-04). The 95th percentile groundwater attenuation factor varies by more than one order of magnitude across the 13 sites for which these statistics could be calculated (ranging from approximately 3E-04 to approximately 8E-03). Of these 13 sites, 3 have 95th percentile values that exceed the 95th percentile of the combined data set when rounded to one significant value; at these 3 sites, however, the 75th percentile values are within a factor of two of the 95th percentile of the combined data set. In general, the intra-site and inter-site variabilities are greater for the groundwater data set than for the subslab soil gas data set. The greater intra-site and inter-site variability in the groundwater attenuation factors, when compared with the subslab soil gas attenuation factors, may be attributed to variability in the depth to groundwater and other subsurface conditions that influence attenuation in the vadose zone. Additionally, differences in groundwater monitoring well construction (e.g., screened intervals), well network layout, and horizontal distance between the respective building and the respective well(s) may also contribute variability.

Table 13. Descriptive statistics summarizing groundwater attenuation factor distributions for individual sites compared with the combined data set after Source Strength Screen (groundwater vapor concentrations > 1,000 times "background").

Statistic	GW > 1,000 X Bkgd	Allepo	Alliant	BillingsPCE	CDOT	Davis	Eau Claire	Endicott	Grants	Hamilton-Sundstrand	Harcros/Tri State	Hopewell Precision	Jackson	LAFB	Lockwood	MADEP 1	MADEP 2	Moffet	Mountain View	Rapid City	Redfield	SCM - Cortlandville	Uncasville	Wall	West Side Corp.
Min	1.0E-07	9.1E-06	2.5E-06	1.0E-06	1.8E-06	4.7E-05	3.6E-06	1.9E-05	1.0E-07	9.6E-06	1.2E-06	2.5E-05		2.9E-06	8.6E-07	1.6E-04		1.3E-06	4.8E-07	9.9E-06	1.7E-06	5.9E-05	3.3E-05	1.4E-06	2.1E-06
5%	3.6E-06			1.1E-05	3.4E-06			2.8E-05	9.7E-07	1.2E-05		1.7E-04		4.0E-06	2.9E-06						7.6E-06	5.9E-05		1.7E-05	1.3E-05
25%	2.3E-05			2.1E-05	9.9E-06			2.8E-05	2.7E-06	5.8E-05		2.9E-04		1.7E-05	1.9E-05						2.8E-05	5.9E-05	3.5E-04	2.9E-05	1.5E-05
50%	7.4E-05		3.7E-06	3.9E-05	2.2E-05		2.5E-04	1.7E-04	1.2E-05	1.0E-04	2.5E-04	5.6E-04	4.7E-04	3.4E-05	8.8E-05		4.0E-05	4.0E-06	3.3E-06	3.1E-05	7.3E-05	3.1E-04	4.8E-04	8.2E-05	3.7E-05
75%	2.0E-04			8.9E-05	1.5E-04			7.0E-04	8.7E-05	1.5E-04		1.2E-03		1.4E-04	2.7E-04						1.5E-04	1.7E-03	6.5E-04	3.2E-04	2.7E-04
95%	1.2E-03			6.8E-04	5.4E-04			1.4E-03	2.9E-04	2.9E-04		7.7E-03		6.8E-04	1.3E-03						4.8E-04	4.2E-03		1.4E-03	4.3E-03
Max	2.1E-02	1.4E-05	1.1E-03	8.0E-04	5.4E-04	4.3E-04	1.9E-03	1.5E-03	2.9E-04	5.2E-04	3.7E-03	7.7E-03		2.3E-03	2.4E-03	1.0E-03		1.9E-05	3.3E-05	4.0E-05	1.8E-03	6.6E-03	1.8E-03	1.1E-02	2.1E-02
Mean	2.8E-04		1.1E-04	1.2E-04	1.1E-04	2.4E-04	7.7E-04	4.3E-04	7.5E-05	1.2E-04	7.1E-04	1.2E-03		1.6E-04	2.6E-04	6.0E-04		7.9E-06	9.7E-06	2.7E-05	1.3E-04	1.1E-03	6.0E-04	4.9E-04	1.1E-03
StdDev	1.0E-03		3.4E-04	2.1E-04	1.7E-04		8.1E-04	4.8E-04	1.1E-04	9.8E-05	1.3E-03	1.8E-03		3.6E-04	4.5E-04			9.3E-06	1.4E-05	1.6E-05	1.9E-04	1.6E-03	5.1E-04	1.7E-03	4.0E-03
95UCL	3.4E-04		2.8E-04	1.9E-04	1.8E-04		1.4E-03	5.7E-04	1.2E-04	1.5E-04	1.7E-03	2.0E-03		2.2E-04	3.5E-04			2.4E-05	2.3E-05	5.4E-05	1.5E-04	1.6E-03	9.2E-04	9.2E-04	2.3E-03
Count All	774	2	12	25	17	2	6	32	14	32	7	17	1	93	63	2	1	3	5	3	329	28	9	43	28
Count >RL	743	1	5	25	17	2	6	22	14	32	7	17	1	93	63	2	1	3	5	3	329	21	9	43	22
Count <RL	31	1	7	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	6

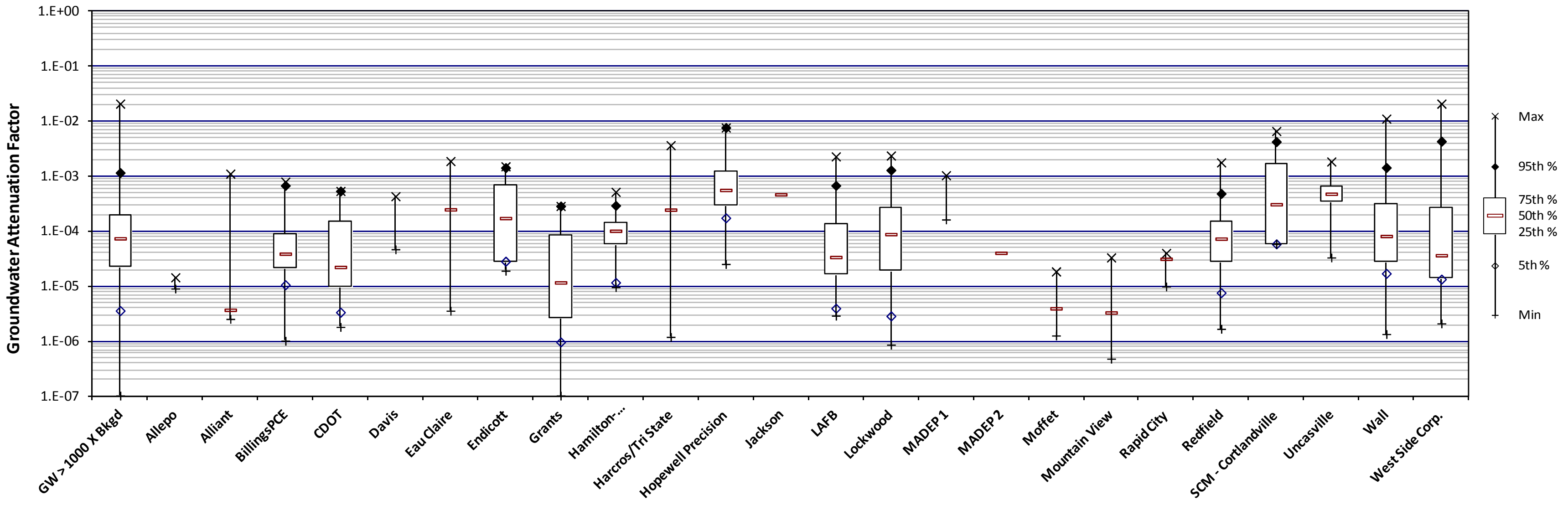


Figure 28. Box-and-whisker plots summarizing groundwater attenuation factor distributions for individual sites compared with the combined data set after Source Strength Screen (groundwater vapor concentrations > 1,000 times "background").

Table 14 provides selected statistics, and **Figure 29** shows the box-and-whisker plots for the groundwater attenuation factors for three soil types. Comparing each descriptive statistic (except for the 25th percentile values) indicates that the attenuation factor values for residences overlying soils classified as "very coarse" are larger than those for residences overlying soils classified as "coarse," which are larger than those for soils classified as "fine." This pattern is consistent with the conceptual model for vapor intrusion; smaller attenuation factors, which indicate greater reduction in vapor concentration, would be expected in vadose zones with finer grained soils, when all other factors (e.g., depth to groundwater, biodegradability of the volatile chemicals) are the same.

Table 14. Descriptive statistics summarizing groundwater attenuation factor distributions for specific soil types after Source Strength Screen.

	Soil Type Below Foundation		
Statistic	**Fine**	**Coarse**	**V.Coarse**
Min	1.0E-07	4.8E-07	2.1E-06
5%	2.3E-06	7.6E-06	1.3E-05
25%	1.9E-05	3.1E-05	2.0E-05
50%	4.6E-05	1.0E-04	1.5E-04
75%	1.4E-04	2.5E-04	6.8E-04
95%	4.5E-04	1.4E-03	4.2E-03
Max	2.4E-03	1.1E-02	2.1E-02
Mean	1.3E-04	3.3E-04	9.7E-04
StdDev	2.4E-04	8.9E-04	3.0E-03
95UCL	1.5E-04	4.1E-04	1.7E-03
Count All	353	369	52
Count >RL	344	359	40
Count <RL	9	10	12
No. of sites	10	15	3

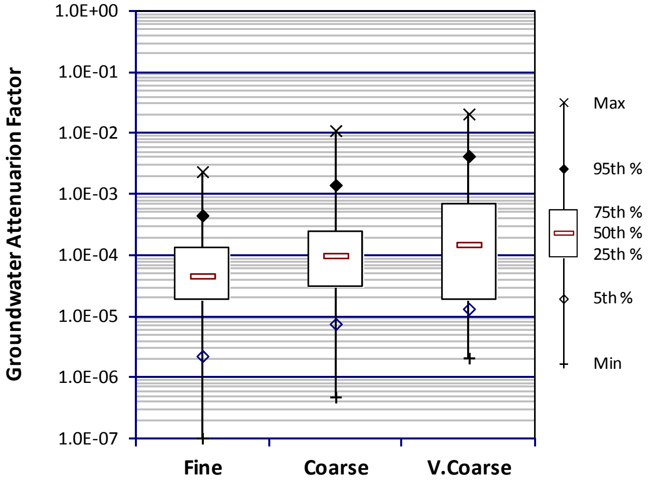


Figure 29. Box-and-whisker plots summarizing groundwater attenuation factor distributions for specific soil types after Source Strength Screen.

Table 15 provides selected statistics, and **Figure 30** shows the box-and-whisker plots for the groundwater attenuation factors for four categories of depth to groundwater. Comparing each descriptive statistic, the attenuation factors generally decrease (i.e., indicate greater reduction in vapor concentration) with increasing depth to groundwater. For example, the 95th and 75th percentile values of the empirical attenuation factors calculated for depth to water less than 1.5 meters are greater (indicating less attenuation/dilution) than those for depth to water between 1.5 and 3 meters. The 95th and 75th percentile attenuation factors continue to decrease for depth to water between 3 and 5 meters and depth to water greater than 5 meters. This pattern is consistent with the conceptual model for vapor intrusion; smaller attenuation factors, which indicate greater reduction in vapor concentration, would be expected in thicker vadose zones (as indicated by greater depths to groundwater), when all other factors (e.g., soil type, biodegradability of the volatile chemicals) are the same.

Table 15. Descriptive statistics summarizing groundwater attenuation factor distributions for various depth to groundwater categories after Source Strength Screen.

	Depth to Groundwater			
Statistic	**< 1.5 m**	**1.5 - 3 m**	**3 - 5 m**	**> 5 m**
Min	3.6E-06	8.6E-07	1.2E-06	1.0E-07
5%	1.6E-05	2.9E-06	1.3E-06	2.9E-06
25%	2.9E-04	3.2E-05	1.4E-05	1.9E-05
50%	6.1E-04	1.2E-04	4.2E-05	4.8E-05
75%	1.5E-03	3.2E-04	2.5E-04	1.6E-04
95%	6.6E-03	2.4E-03	1.7E-03	6.4E-04
Max	7.7E-03	4.2E-03	3.7E-03	1.1E-02
Mean	1.2E-03	3.9E-04	3.3E-04	2.1E-04
StdDev	1.6E-03	7.2E-04	6.6E-04	8.5E-04
95UCL	1.6E-03	5.3E-04	4.4E-04	3.2E-04
Count All	36	77	97	181
Count >RL	36	76	83	171
Count <RL	0	1	14	10
No. of sites	4	5	9	6

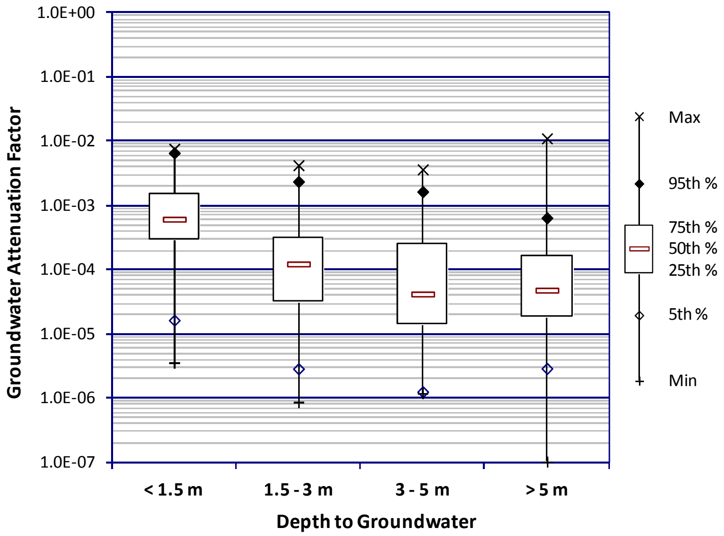


Figure 30. Box-and-whisker plots summarizing groundwater attenuation factor distributions for various depth to groundwater categories after Source Strength Screen.

Table 16 provides selected statistics and **Figure 31** shows the box-and-whisker plots for the groundwater attenuation factors for four of the most commonly encountered chlorinated hydrocarbons in the combined data set, each of which was a chemical of concern at five or more sites and with at least 36 values after screening. The median groundwater attenuation factor for these four volatile chemicals fell within a range of approximately 3E-05 to approximately 1E-04. Likewise, the 95th percentile groundwater attenuation factor for these four volatile chemicals fell within a range of approximately 5E-04 to approximately 2E-03. Similar relationships were observed for the subslab soil gas attenuation factors. These observations are consistent with the conceptual model of vapor intrusion, which predicts that chemicals with similar fate-and-transport properties, such as CHCs, are expected to have similar attenuation factor values. The variability that is observed among these chemicals may be attributed to analytical uncertainty, particularly at concentrations near the RLs for these substances.

5.3 Exterior Soil-Gas-to-Indoor-Air Attenuation Factors

Empirical exterior soil gas attenuation factors are calculated by dividing an indoor air concentration measured in a building (C_{IA}) by the corresponding soil gas concentration measured exterior to the same building (i.e., Equation 3 with the soil gas concentration [C_{sg}] as the source concentration [C_{SV}]). As indicated by Equations 4a and 4b, the empirical exterior soil gas attenuation factor is expected to be influenced by building characteristics, including potential indoor sources of VOCs, ($AF_{EMP,bldg}$) and soil characteristics that influence attenuation through the vadose zone (AF_{soil}).

Table 17 provides selected statistics, and **Figure 32** shows box-and-whisker plots for individual sites compared with the combined set of screened exterior soil gas attenuation factors. For the combined data set (i.e., all sites, all CHCs), at a source-strength filter level of 50 times "background," the median exterior soil gas attenuation factor is approximately 4E-03 (0.004), and the 95th percentile value is approximately 3E-01 (0.3) (both rounded to one significant figure). The median exterior soil gas attenuation factor is slightly larger, and the 95th percentile value is substantially larger than the respective statistics for the subslab soil gas attenuation factors (see **Table 10** and **Figure 25**). This is contrary to the conceptual model for vapor intrusion, which predicts that the exterior soil gas attenuation factor for a given building is expected to be smaller than the subslab soil gas attenuation factor for that building, because the former includes an additional contribution from attenuation through the vadose zone (AF_{soil}). Potential explanations for this unexpected finding include:

- The distributions of building-specific characteristics and subsurface conditions (e.g., soil type) may not be identical between the two types of vapor attenuation factors. For example, there are more subslab soil gas attenuation factors (about five times as many) in the database compared with exterior soil gas attenuation factors and only about half the sites with exterior soil gas data also have subslab soil gas data.
- In some cases, soil gas samples collected exterior to a building may not be representative of the source concentrations contributing to vapor intrusion (see **Figure 6**). Errors of this sort may be minimized by developing a sound conceptual model of vapor source(s) and migration and collecting a sufficient number of well-located samples to characterize the spatial distribution and temporal variability in the subsurface vapor concentrations, in accordance with the conceptual model.

Table 16. Descriptive statistics summarizing groundwater attenuation factor distributions for specific VOCs after Source Strength Screen.

Abbreviations: TCE = trichloroethylene; PCE = tetrachloroethylene; 11DCE = 1,1-dichloroethylene; 12DCE = 1,2-dichloroethylene; CHC = chlorinated hydrocarbon.

		Chemical				
Statistic	**GW > 1000 x Bkgd**	**TCE**	**PCE**	**11DCE**	**cis12DCE**	**Other CHCs**
Min	1.0E-07	4.8E-07	1.0E-07	1.7E-06	8.6E-07	1.1E-06
5%	3.6E-06	3.6E-06	1.7E-06	6.4E-06	1.8E-06	2.0E-05
25%	2.3E-05	1.7E-05	2.7E-05	2.6E-05	1.6E-05	1.0E-04
50%	7.4E-05	1.0E-04	6.8E-05	7.0E-05	2.7E-05	1.5E-04
75%	2.0E-04	4.2E-04	3.2E-04	1.5E-04	1.3E-04	2.6E-04
95%	1.2E-03	2.4E-03	1.5E-03	4.7E-04	1.5E-03	5.4E-04
Max	2.1E-02	7.7E-03	2.1E-02	1.8E-03	1.9E-03	1.9E-03
Mean	2.8E-04	4.6E-04	5.1E-04	1.3E-04	1.8E-04	2.6E-04
StdDev	1.0E-03	9.7E-04	2.1E-03	1.9E-04	4.0E-04	3.9E-04
95UCL	3.4E-04	5.8E-04	8.0E-04	1.4E-04	2.9E-04	4.0E-04
Count All	774	190	138	388	36	22
Count >RL	743	170	132	383	36	22
Count <RL	31	20	6	5	0	0
No. of sites	24	16	8	6	5	3

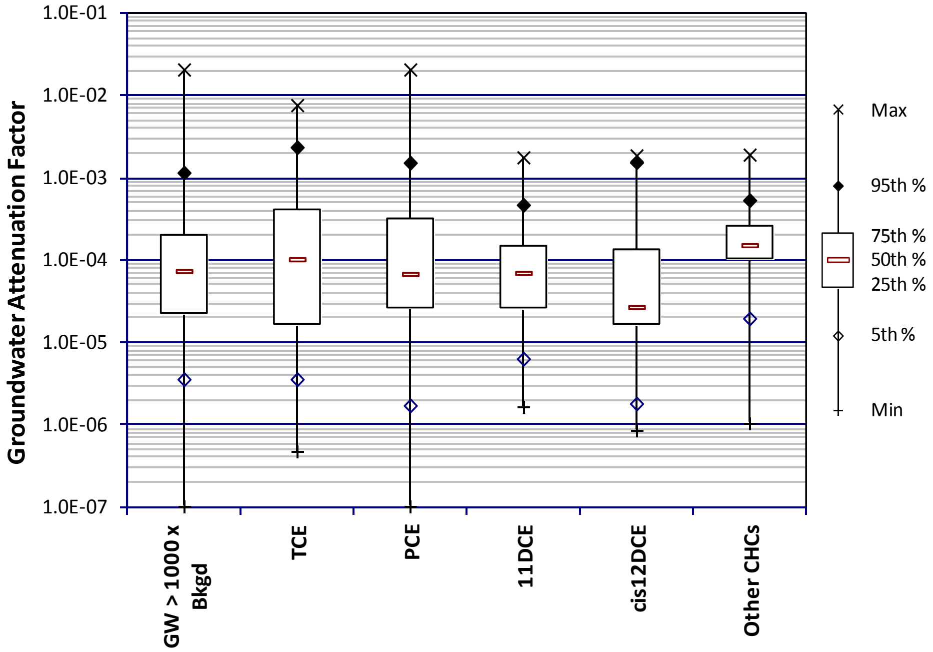


Figure 31. Box-and-whisker plots summarizing groundwater attenuation factor distributions for specific VOCs after Source Strength Screen.

Abbreviations: TCE = trichloroethylene; PCE = tetrachloroethylene; 11DCE = 1,1-dichloroethylene; 12DCE = 1,2-dichloroethylene; CHC = chlorinated hydrocarbon.

Table 17. Descriptive statistics summarizing exterior soil gas attenuation factor distributions for individual sites after Source Strength Screen (exterior soil gas concentrations > 50 times "background").

		Site										
Statistic	**SG > 50X Bkgd**	**Alliant**	**Endicott**	**Georgetown**	**Grants**	**Harcros/Tri State**	**Jackson**	**MADEP1**	**Mountain View**	**SCM - Cortlandville**	**Uncasville**	**West Side Corporation**
Min	5.0E-06		4.2E-05	3.2E-03	4.1E-04	5.0E-06	1.3E-04	9.0E-03	1.2E-05	6.0E-04	7.6E-05	4.2E-04
5%	7.6E-05		6.0E-05		1.4E-03					3.1E-03		
25%	6.0E-04		2.8E-04		6.3E-03	2.7E-04				7.5E-03	1.6E-02	5.2E-04
50%	3.8E-03	7.2E-03	1.3E-03	6.7E-03	4.0E-02	1.3E-03			6.1E-04	3.0E-02	1.8E-02	8.5E-04
75%	2.7E-02		2.1E-03		1.4E-01	8.3E-03				8.9E-02	2.8E-02	2.5E-03
95%	2.5E-01		4.8E-03		1.1E+00					2.5E-01		
Max	1.3E+00		7.5E-03	8.3E-03	1.3E+00	3.4E-02	2.3E-04	2.7E-02	8.4E-03	2.5E-01	8.9E-02	6.8E-03
Mean	5.0E-02		1.6E-03	6.1E-03	1.6E-01	7.6E-03	1.8E-04	1.8E-02	3.0E-03	5.4E-02	3.0E-02	1.9E-03
StdDev	1.7E-01		1.8E-03	2.6E-03	3.2E-01	1.3E-02			4.7E-03	6.8E-02	3.4E-02	2.0E-03
95UCL	7.8E-02		2.1E-03	1.0E-02	2.7E-01	1.9E-02	4.7E-04		1.1E-02	8.5E-02	6.3E-02	3.1E-03
Count All	106	1	33	3	26	6	2	2	3	15	5	10
Count >RL	106	1	33	3	26	6	2	2	3	15	5	10
Count <RL	0	0	0	0	0	0	0	0	0	0	0	0

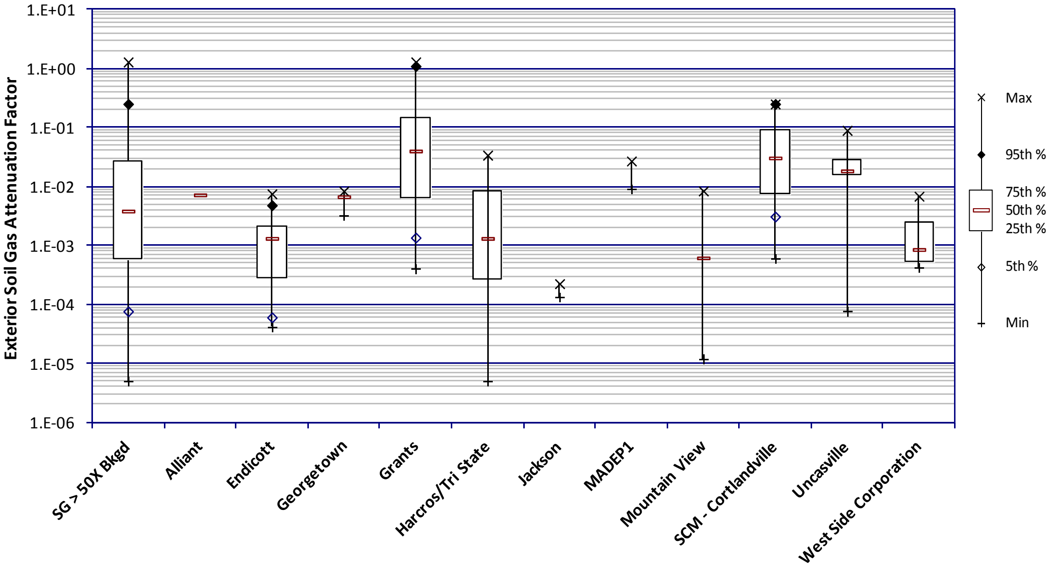


Figure 32. Box-and-whisker plots summarizing exterior soil gas attenuation factor distributions for individual sites after Source Strength Screen (exterior soil gas concentrations > 50 times "background").

Table 17 and **Figure 32** demonstrate intra-site and inter-site variability in the exterior soil gas attenuation factor. The inter-quartile range (i.e., the range from the 25th to 75th percentile values) spans more than one order of magnitude for three of the six sites for which these statistics could be calculated. The range from the 5th to 95th percentile values exceeds two orders of magnitude for all three sites for which these statistics could be calculated. **Figure 32** also demonstrates inter-site variability in the exterior soil gas attenuation factor. The median exterior soil gas attenuation factor ranged by almost two orders of magnitude across the eight sites (from approximately 9E-04 to approximately 4E-02). The 95th percentile subslab soil gas attenuation factor ranged by more than two orders of magnitude across the three sites for which these statistics could be calculated (from approximately 5E-03 to approximately 1). These data in general show greater intra-site and inter-site variability in the exterior soil gas attenuation factors than in the subslab soil gas attenuation factors, which is expected and may be attributed to variability in the vertical and horizontal distances between the exterior soil gas sampling location and the building and other subsurface conditions that influence attenuation through the vadose zone. Differences in soil gas collection methods and gas sampling network layout may also contribute variability.

Because of the relatively limited number of exterior soil gas attenuation factors and concerns that soil gas samples collected exterior to a building may not be representative of the source concentrations contributing to vapor intrusion, the **Source Screen Data Set** was not further differentiated by chemical, building type, or soil type.

5.4 Crawlspace-to-Indoor-Air Attenuation Factors

Empirical crawlspace attenuation factors are calculated by dividing an indoor air concentration measured in a building (C_{IA}) by the measured crawlspace concentration in the same building (i.e., Equation 3 with the crawlspace concentration as the source concentration [C_{SV}]). Like the subslab soil gas attenuation factor, the empirical crawlspace attenuation factor is expected to be influenced solely by building characteristics, including potential indoor sources of VOCs. It is not expected to depend on soil characteristics that influence attenuation through the vadose zone (AF_{soil}).

Table 18 provides selected statistics, and **Figure 33** shows box-and-whisker plots for individual sites compared with the combined set of screened crawlspace soil gas attenuation factors. In contrast to the other media evaluated in this report, which were screened using a source-strength filter, the **Indoor Air Screen** (see Section 4.4.1) was found to be most effective for the crawlspace data. For the combined data set (i.e., all sites, all CHCs), when indoor air concentrations are more than one times "background," the median crawlspace attenuation factor is approximately 4E-01 (0.4), and the 95th percentile value is approximately 9E-01 (0.9). In addition, the 25th percentile value is only 2E-01 (0.2). These results suggest that generally little attenuation occurs between the crawlspace and indoor air space. Alternatively, these results could be taken to indicate that air exchange between the two spaces leads to approximate equilibration in the concentrations.

Because of the relatively limited number of crawlspace attenuation factors, the **Indoor Air Screen Data Set** was not further differentiated by chemical.

Table 18. Descriptive statistics summarizing crawlspace attenuation factor distributions for individual sites after Indoor Air Screen (indoor air concentrations > one times "background").

Statistic	IA > Bkgd	Site			
		Grants	Jackson	LAFB	Lockwood
Min	5.7E-02	1.7E-01		5.7E-02	2.2E-01
5%	1.0E-01			6.5E-02	
25%	2.2E-01			2.7E-01	
50%	3.9E-01	3.9E-01	5.0E-01	4.2E-01	2.2E-01
75%	6.9E-01	8.3E-01		8.3E-01	
95%	9.0E-01			9.0E-01	
Max	9.2E-01	9.2E-01		9.2E-01	2.9E-01
Mean	4.6E-01	4.8E-01		4.8E-01	2.4E-01
StdDev	2.8E-01	3.0E-01		2.9E-01	4.2E-02
95UCL	5.3E-01	7.0E-01		5.7E-01	3.2E-01
Count All	41	7	1	30	3
Count >RL	41	7	1	30	3
Count <RL	0	0	0	0	0

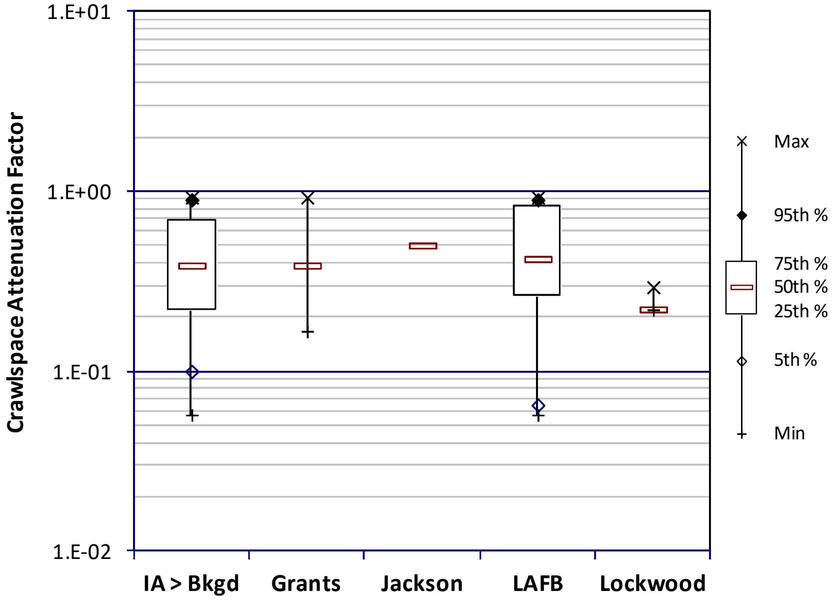


Figure 33. Box-and-whisker plots summarizing crawlspace attenuation factor distributions for individual sites after Indoor Air Screen (indoor air concentrations > one times "background").

6.0 Summary and Conclusions

The data contained in EPA's vapor intrusion database were compiled to help understand the vapor intrusion pathway and particularly, the attenuation that may be observed when vapors migrate from subsurface sources into indoor spaces. After removing data that do not meet certain quality criteria and data likely to be influenced by background sources, the distributions of remaining attenuation factors were analyzed graphically and statistically. The analyses presented in this report show that it is important to consider the influence of background sources on empirical attenuation factors in order to distinguish impacts due to vapor intrusion.

EPA's vapor intrusion database presents the most comprehensive compilation of vapor intrusion data for chlorinated hydrocarbons in residences available at this time. The observations summarized here based on empirical attenuation factor distributions are considered representative of vapor intrusion of CHCs from subsurface sources into buildings for most conditions. Nevertheless, it is important to consider that the database, although relatively large, reflects only a subset of the hundreds of vapor intrusion sites identified nationwide. Therefore, the statistical distributions may change as data are added to the database, and the attenuation factors in this report may not apply to new sites with significantly different subsurface and building conditions.

In summary, **Table 19** and **Figure 34** present and compare the distributions of the attenuation factors (groundwater, exterior soil gas, subslab soil gas, and crawlspace) that remain after applying the respective source strength and indoor air screens considered most effective at reducing the influence of background contributions to indoor air concentrations, for reasons described in Section 4.0. These data demonstrate that the attenuation factor distributions obtained for groundwater, subslab soil gas, and crawlspaces are consistent with the conceptual model for vapor intrusion, which predicts that greater attenuation is expected with greater depths to the vapor sources or vapor samples (Johnson and Ettinger, 1991). As shown in **Table 19** and **Figure 34**, the paired groundwater–indoor air data generally exhibit greater attenuation (lower attenuation factors) than the paired subslab soil gas–indoor air data, which in turn exhibit greater attenuation than the paired crawlspace–indoor air data.

Greater attenuation generally is expected for groundwater sources, where vapors must migrate through both the capillary fringe and soils in the unsaturated zone. Attenuation across the capillary fringe is unique to the groundwater attenuation factors (i.e., does not affect exterior soil gas, subslab soil gas, or crawlspace attenuation factors), so a broader range in groundwater attenuation factors is to be expected than may be observed for other types of attenuation factors. In addition, one might also expect to observe greater variability in the groundwater attenuation factors than in the subslab soil gas attenuation factors owing to variability in the depth to groundwater and other subsurface conditions that could influence attenuation through the vadose zone, but which are not expected to influence the subslab attenuation factors. Differences in groundwater monitoring well construction (e.g., screened intervals), well network layout, and horizontal distance between the respective building and the respective well(s) may also contribute variability. With the exception of the exterior soil gas data, the attenuation factor relationships developed in this report are generally consistent with these expectations, based upon the conceptual model for vapor intrusion.

Table 19. Descriptive statistics summarizing attenuation factor distributions for groundwater, exterior soil gas, subslab soil gas, and crawlspace vapor after application of the database screens considered most effective at minimizing the influence of background sources on indoor air concentrations.

Statistic	Groundwater (GW > 1,000X Bkgd)	Exterior Soil Gas (SG > 50X Bkgd)	Subslab Soil Gas (SS > 50X Bkgd)	Crawlspace (IA > Bkgd)
Min	1.0E-07	5.0E-06	2.5E-05	5.7E-02
5%	3.6E-06	7.6E-05	3.2E-04	1.0E-01
25%	2.3E-05	6.0E-04	1.5E-03	2.2E-01
50%	7.4E-05	3.8E-03	2.7E-03	3.9E-01
75%	2.0E-04	2.7E-02	6.8E-03	6.9E-01
95%	1.2E-03	2.5E-01	2.6E-02	9.0E-01
Max	2.1E-02	1.3E+00	9.4E-01	9.2E-01
Mean	2.8E-04	5.0E-02	9.2E-03	4.6E-01
StdDev	1.0E-03	1.7E-01	5.0E-02	2.8E-01
95UCL	3.4E-04	7.8E-02	1.3E-02	5.3E-01
Count All	774	106	431	41
Count >RL	743	106	411	41
Count <RL	31	0	20	0
No. of sites	24	11	12	4

Note: The applied database screens are groundwater (vapor) concentrations > 1,000X "background," exterior soil gas > 50X "background," subslab soil gas > 50X "background," and for crawlspace, indoor air concentrations > 1X "background."

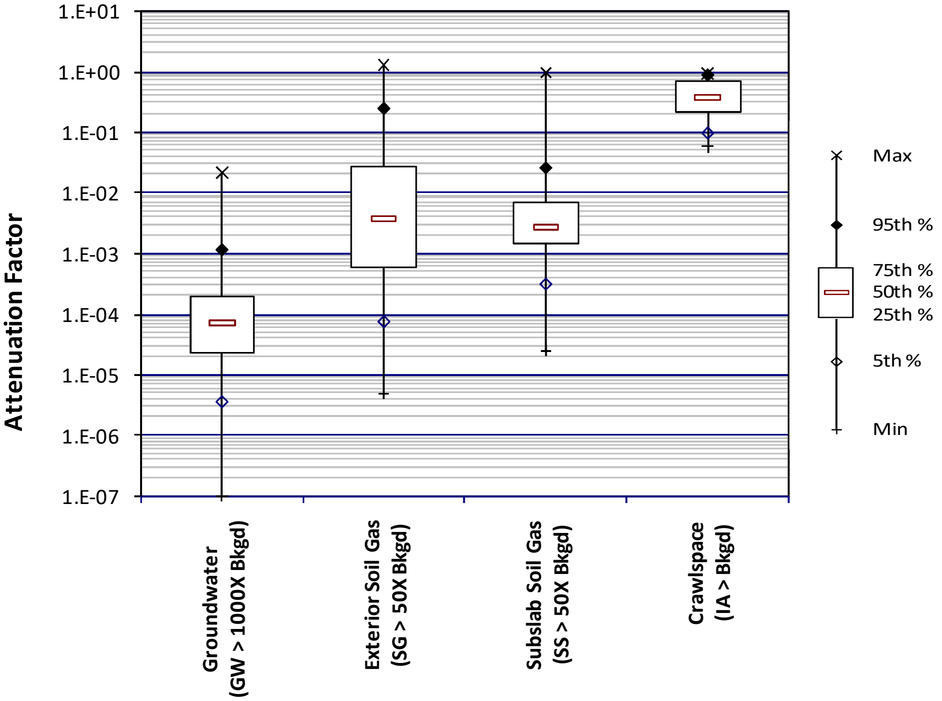


Figure 34. Box-and-whisker plots summarizing attenuation factor distributions for groundwater, exterior soil gas, subslab soil gas, and crawlspace vapor after application of the database screens considered most effective at minimizing the influence of background sources on indoor air concentrations.

The ranges of attenuation factors obtained for each medium (groundwater, exterior soil gas, subslab soil gas, and crawlspace) after screening to minimize the influence of background sources on indoor air concentrations nevertheless span several orders of magnitude. Some of this variability is unquestionably due to the inherent variability in media concentrations and vapor intrusion processes. Additional variability likely is introduced by differences in building characteristics and localized geologic conditions. Variability may also be introduced by non-representative subsurface samples—samples that because of sampling errors or other sampling issues may under- or over-represent the vapor source concentrations. The observed variability in attenuation factors is thus expected given the variability in media concentrations, subsurface conditions, and building characteristics represented by the data compiled in the database.

6.1 Subslab Soil Gas Attenuation Factors

The source-strength screening criterion of 50 times "background" was used to extract the subset of subslab soil gas attenuation factors for CHCs in residential settings because it represented the best screening criterion for minimizing the influence of background sources on the data. For this combined data set (i.e., all sites, all CHCs), the following descriptive statistics were obtained (to one significant digit):

	Median (50th percentile)	95th Percentile
All residences	3E-03 (0.003)	3E-02 (0.03)
Residences with basements	3E-03 (0.003)	3E-02 (0.03)
Residences with slab-on-grade	3E-03 (0.003)	1E-02 (0.01)

These comparisons indicate that the subslab soil gas attenuation factors for residences with basements are generally similar to those for residences with a slab-on-grade foundation. As expected, the median subslab soil gas attenuation factors for the four most commonly encountered CHCs in the combined data set were quite similar, as were the 95th percentile values:

	Median (50th percentile)	95th Percentile
Trichloroethylene (TCE)	3E-03 (0.003)	3E-02 (0.03)
Tetrachloroethylene (PCE)	2E-03 (0.002)	3E-02 (0.03)
1,1,1,-trichloroethane (TCA)	4E-03 (0.004)	1E-02 (0.01)
1,1-dichloroethylene (1,1-DCE)	2E-03 (0.002)	2E-02 (0.02)

Importantly, these empirical subslab soil gas attenuation factors are supported by theoretical calculations. Finally, Table 10 and Figure 25 demonstrate intra-site variability and inter-site variability in the subslab soil gas attenuation factor.

6.2 Groundwater Attenuation Factors

The source-strength screening criterion of 1,000 times "background" was used to extract the subset of groundwater attenuation factors for CHCs in residential settings because it represented the best screening criterion for minimizing the influence of background sources on the data. For this combined data set (i.e., all sites, all CHCs), the following descriptive statistics were obtained (to one significant digit):

	Median (50th percentile)	95th Percentile
All soil types and water depths	7E-05 (0.00007)	1E-03 (0.001)
Fine soil type	5E-05 (0.00005)	5E-04 (0.0005)
Coarse soil type	1E-04 (0.0001)	1E-03 (0.001)
Very coarse soil type	2E-04 (0.0002)	4E-03 (0.004)
Depth to water < 1.5 m	6E-04 (0.0006)	7E-03 (0.007)
Depth to water 1.5–3 m	1E-04 (0.0001)	2E-03 (0.002)
Depth to water 3–5 m	4E-05 (0.00004)	2E-03 (0.002)
Depth to water > 5 m	5E-05 (0.00005)	6E-04 (0.0006)

These comparisons indicate that the groundwater attenuation factors for residences tend to be smaller (indicating greater attenuation in vapor concentrations during subsurface migration) for fine-grained soils and larger for very coarse-grained soils, which is consistent with the conceptual model for vapor intrusion; more attenuation would be expected for vapor migration through fine-grained vadose zones, when all other factors (e.g., depth to groundwater, biodegradability of the volatile chemicals) are the same. These comparisons also indicate that the groundwater attenuation factors for residences tend to be smaller (indicating greater attenuation in vapor concentrations during subsurface migration) for deeper groundwater tables than for shallow groundwater tables, which is also consistent with the conceptual model for vapor intrusion. As expected, the median groundwater attenuation factor for the four most commonly encountered CHCs in the combined data set varied by less than an order of magnitude, as did the 95th percentile values:

	Median (50th percentile)	95th Percentile
Trichloroethylene (TCE)	1E-04 (0.0001)	2E-03 (0.002)
Tetrachloroethylene (PCE)	7E-05 (0.00007)	2E-03 (0.002)
1,1-dichloroethylene (1,1-DCE)	7E-05 (0.00007)	5E-04 (0.0005)
Cis-1,2-dichloroethylene (cis-1,2-DCE)	3E-05 (0.00003)	2E-03 (0.003)

These values are at least an order of magnitude smaller than the equivalent statistics for the combined set of subslab soil gas attenuation factors (indicating greater reduction in vapor concentrations during vapor migration from groundwater sources and entry into residences), which is consistent with the conceptual model for vapor intrusion.

Finally, Table 13 and Figure 28 demonstrate intra-site variability and inter-site variability in the groundwater attenuation factors, which are greater than the intra-site and inter-site variability seen in the subslab soil gas attenuation factors.

6.3 Exterior Soil Gas Attenuation Factors

The source-strength screening criterion of 50 times "background" was used to extract the subset of exterior soil gas attenuation factors for CHCs in residential settings because it represented the best screening criterion for minimizing the influence of background sources on the data. For this combined data set (i.e., all sites, all CHCs), the following descriptive statistics were obtained (to one significant digit):

	Median (50th percentile)	95th Percentile
All residences	4E-03 (0.004)	3E-01 (0.3)

The median soil gas attenuation factor is slightly larger than the median subslab soil gas attenuation factor (0.004 versus 0.003, respectively), comparing the respective combined **Source Screen Data Sets**. The 95th percentile soil gas attenuation factor is substantially larger than the 95th percentile subslab soil gas attenuation factor (0.3 versus 0.03, respectively). These results are contrary to the conceptual model for vapor intrusion, which predicts that the exterior soil gas attenuation factor for a given building would be expected to be substantially smaller than the subslab soil gas attenuation factor for a given building, because the former includes an additional contribution from attenuation through the vadose zone (AF_{soil}). This suggests that a substantial proportion of the exterior soil gas data in the database may not be representative of soil gas concentrations directly underneath a building, which also was suggested by a comparison (in Section 3.2 and **Figure 6**) of exterior soil gas to subslab soil gas concentrations for buildings where both types of samples were collected. These observations suggest that soil gas sampling methods may need to be further improved and standardized for vapor intrusion investigations.

Finally, **Table 17** and **Figure 32** demonstrate intra-site and inter-site variability in the exterior soil gas attenuation factor. These data in general show greater intra-site and inter-site variability in the exterior soil gas attenuation factors than in the subslab soil gas attenuation factors, which is expected.

6.4 Crawlspace Attenuation Factors

The **Indoor Air Screen Data Set** was used to extract the subset of crawlspace attenuation factors for CHCs in residential settings because it represents the best screening criterion for minimizing the influence of background sources on the data. For this combined data set (i.e., all sites, all CHCs), the following descriptive statistics were obtained (to one significant digit):

	Median (50th percentile)	95th Percentile
All residences	4E-01 (0.4)	9E-01 (0.9)

These results suggest that little attenuation generally occurs between the crawlspace and indoor air space. Alternatively, these results could be taken to indicate that air exchange between the two areas leads to approximate equilibration in the concentrations.

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Appendix A

Peer Review Report

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Appendix A. Document Development and Peer Review

This appendix describes the development and review process for EPA 530-R-10-002, EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings. The document was primarily developed by Dr. Helen Dawson of the U.S. Environmental Protection Agency (EPA), in response to the need to update the empirical attenuation factors that are part of the Appendix F of the Office of Solid Waste and Emergency Response's (OSWER's) Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (EPA, 2002) (Draft VI Guidance).

Since 2002, EPA has designed, developed, and managed a database to store and analyze vapor concentration data collected at sites in North America that have been investigated for potential vapor intrusion. A preliminary draft report about this database, based on data compiled as of 2008 (EPA 2008), was subject to extensive internal Agency review, including Regional review and review by other EPA programs and review by members of an expert panel that provided support to OSWER. Additionally, the report was subjected to EPA's formal external peer-review process.

A.1 Internal EPA Review

After initial review by the EPA members of the Vapor Intrusion Guidance Team, EPA's Vapor Intrusion Forum (VIF) and an expert panel reviewed the preliminary report in 2009. The VIF is a group of EPA environmental professionals involved in vapor intrusion assessment, including members from EPA Regions, OSWER, and the Office of Research and Development. The expert panel that provided support to OSWER comprised the following individuals:

- Henry Schuver, Office of Resource Conservation and Recovery, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency
- William Wertz, formerly Chief, Engineering Geology Section, New York State Department of Environmental Conservation, New York
- Ian Hers, Senior Consultant, Golder Associates, Burnaby, British Columbia, Canada
- Jeffrey P. Kurtz, Senior Scientist, EnviroGroup Limited, Centennial, Colorado

In response to the comments from VIF and the expert panel, Dr. Dawson and the Vapor Intrusion Guidance Team made final edits to the document from February 2010 through February 2012. In February 2012, the document received final EPA management and legal review prior to its finalization.

A.2 EPA Peer Review

From June to August 2009, the document was subjected to EPA's external peer review process, where it was reviewed by four experts in the collection, use, and analysis of sub-surface contamination and vapor intrusion data (Robin Davis, Utah Department of Environmental Quality; Philip Dixon, Iowa State University; James Harrington, New York State Department of

Environmental Conservation; and Mart Oostrom, Pacific Northwest Laboratory). This peer review panel was selected to collectively provide the following expertise:

- Designing and conducting vapor intrusion investigations involving measurement of volatile organic compounds (VOCs) in the soil gas, groundwater, indoor air, and outdoor air.
- Indoor air, subslab, and soil gas sampling and analytical methods used in vapor intrusion investigations and in indoor air quality surveys for VOCs, including installing and sampling subslab and soil gas probes.
- Interpreting the results of vapor intrusion investigations, particularly focusing on the accurate determination of the attenuation factors observed.
- Statistical methods for dealing with censored data (i.e., measurements below the reporting limit) when analyzing large environmental data sets.
- Assembling and using environmental data sets for regulatory purposes, in particular in relation to vapor intrusion evaluations.
- Working familiarity with Microsoft Excel. (Excel expertise was needed to evaluate the database.)

Environmental Management Support, Inc. managed the external peer review process and provided a compilation of the comments. In response to the comments of the peer reviewers, Dr. Dawson and the Vapor Intrusion Guidance Team edited and revised the document from February 2010 through February 2012.

A.3 Peer Review Charge Questions

The following general charge questions were developed by EPA for the peer review of the preliminary draft:

1. Is the document clear with respect to objectives and purpose? Is there an adequate problem statement? Are the stated objectives and purpose met?

2. Are the strengths and limitations of the study clearly laid out in the documentation?

3. Are you aware of any additional information that would significantly reduce key uncertainties, change the overall findings of, or significantly improve the document? For example, are there other good studies or sources on vapor intrusion attenuation data that you are aware of that were not included?

Specific peer review charge questions consisted of the following:

4. Are the methods used to collect, compile, document, and ensure the quality of the vapor intrusion data adequate and were the methods used appropriately? Is the discussion understandable?

5. Were measurements below reporting limits appropriately treated and considered in the data analysis?

6. Was the potential for indoor sources of background VOCs appropriately considered when interpreting results? Is the method used for screening and filtering data to identify real instances of vapor intrusion sound? Is it clearly documented? Are there alternative approaches that should be used or considered? What might be possible impacts of any alternative methods on the report conclusions?

7. Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation? Is the discussion on the use of the data understandable? Are there alternative approaches that may provide additional insights?

A.4 Peer Review Input

Attachment A-1 is a summary matrix of the peer review comments about the preliminary draft report (EPA, 2008). The matrix organizes the comments and recommendations by commenter, charge question, and document section. Attachment A-2 includes the complete set of comments as submitted by each commenter. These comments were considered and addressed as appropriate in this revised document.

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Attachment A-1

Vapor Intrusion Database Peer Review Comment Matrix

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Table A-1. Robin Davis—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
1				Is the document clear with respect to objectives and purpose? No. The document states no purpose and objectives, and is unclear in statements made in the document that might even allude to purpose and objectives. There should be a section that clearly states the purpose and objective, otherwise, practitioners won't know why they would be reading it. There are only allusions of any purpose or objective in section 7.0, Summary and Conclusions," page 36, paragraph 1 where there is discussion helping environmental professional understand the VI pathway and attenuation from subsurface to indoor air. Paragraph 3 alludes to an objective: understanding influences of contaminant concentrations in background air. I agree that this data analysis may be useful for chlorinated VOCs (CVOCs), but the data analyses are not at all representative or useful for petroleum hydrocarbon (PHCs).
1				EPA OSWER's Draft VI Guide (Nov. 2002) wisely cautioned against its use at PHC sites because PHC is known to biodegrade. The Guide in fact recommended that PHC be studied separately (which is being done at a much greater rate than for CVOCs). EPA OSWER should use this current opportunity to issue a similar but stronger and more clearly and definitively articulated statement that this document does not have sufficient or meaningful PHC data to draw any statistical conclusion. I strongly advise that PHC be removed from this document. I have studied the PHC data in this EPA d-base and from hundreds of other PHC sites. I have evaluated these data subjectively and know and understand anomalies, I know, for example that the PHC data used in the EPA d-base and shown in Figure 1 all fall well below the line in Figure 1. I also know that for some of the sub-slab and exterior SG exhibit very low benzene SG concentrations (e.g., Stafford Bldgs 3, 22, 14 and 18, and Mt. Holly 91 and 103 Hulme St.).
1				Enough high-quality PHC data have been collected to show that exterior SG sampling is representative and avoids unnecessary, costly and intrusive sub-slab sampling. I therefore cannot accept any suggestion that exterior soil gas (SG) sampling for PHC is not representative and that every site would require sub-slab SG sampling.
1				Is there an adequate problem statement? No. There is no problem statement at all. My suggestion for one [problem statement] would include discussion of the following: 1) CVOCs are in many if not most consumer products and constitute the majority of VI sites); 2) VI from subsurface sources can be difficult to determine because of influence by contaminants in background air, especially at low levels in the subsurface and especially for CVOCs; 3) CVOCs, which are not readily degradable and have toxic by-products have been evaluated for VI along with PHC, which can influence the results of data analysis because: PHC is biodegraded to innocuous by-products and causes VI only under extreme conditions (very high concentrations in close proximity to building foundations); 4) More data are needed to better understand CVOC VI, 5) Exterior SG sampling for CVOCs may not be representative and; 6) While PHC sites are usually very well-characterized, CVOC sites are often not because, since CVOCs are not very degradable, they often form large plumes widespread in extent.
1				Are the stated objectives and purposes met? No because there are no stated purpose and objectives. This is troubling because is shows that this document is not only not useful, it erroneously implies that PHCs behave and intrude enclosed spaces in the same way that CVOCs do.

Table A-1. Robin Davis—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
2				No. Mention of strengths and limitations is dispersed throughout the document, which makes reading this document tedious and leaving one to question its value. There is little mention of substantial limitation until Conclusion, sentence 4. Discussion of strengths and limitations needs its own section and should include discussion of: Strengths: 1) Although limited, the data show that CVOCs constitute majority of VI sites; 2) Knowledge that PHC biodegrades (EPA 1999) and its associated vapors rarely intrude buildings unless high source strengths lie within about 5 feet beneath a building (Davis, 2009; McHugh, et al, 2009 in press). Limitations 1) The database clearly includes background influences and <RL or very low SG concentrations; 2) contains too small a data set of PHC (only 3%) to warrant statistical analysis much less inclusion in this OSWER document. In general, the current data are difficult to evaluate for VI investigations because of background influence and comparison to very low concentrations; 3) Site characterization at CVOC sites is often not thorough, whereas PHC sites are well-characterized because the plumes are smaller due to biodegradation.
3				Yes. There are abundant subsurface-only PHC data that are not included in the EPA database that show rapid biodegradation and attenuation by many orders of magnitude, and that PHC sites only cause VI when source concentrations are very high and in close proximity to building foundations. The document would be greatly improved by removing PHC from the analyses because unnecessary alarm to property occupants would be avoided and expenditures of limited financial resources would be greatly reduced. There are many good studies on PHC sites that have high-quality data, sites are very well-characterized, and subsurface SG attenuation is very strong and vapors are often completely attenuated within a few feet above even very strong sources.
4				While the discussion is understandable, the application is objectionable because: 1) the document admits that data quality at some sites is low, sites may not be well-characterized, and source strengths beneath buildings may not be known. Poor site characterization is often the case for CVOCs but not for PHCs. I think the document should exclude data from sites that are not well-characterized and all data from PHC sites. Also, I entirely disagree that the small PHC data set can be used to make any analysis at all about PHC, and; 2) On page 12 it is stated that exterior SG may be not be representative (which is not supportable by this document and a point on which I entirely disagree), then on page 24, AFs are calculated using those exterior points.
5				Probably OK for CVOCs but not for PHCs because all of the PHC data show biodegradation beneath and exterior to buildings if sufficient clean overlying soil exists. Only Stafford Bldg 73 w/basement has VI not because of a preferential anoxic zone due to the slab but because of the close proximity of the basement to the source and insufficient thickness of clean overlying soil.
6				Was the potential for indoor sources of background VOCs appropriately considered when interpreting results? No. On page 13, the reference to Table 5 shows that for most chemicals-including tetrachloroethylene; 1,1,1-trichloroethane; and the petroleum hydrocarbons-the indoor air concentrations at the vapor intrusion sites in the database are roughly equivalent in range to the background indoor air concentrations in Table 4. This seems to be saying that, based on the limited data in the database, there is no evidence that petroleum hydrocarbons are causing vapor intrusion.

Table A-1. Robin Davis—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
6				Is the method used for screening and filtering data to identify real instances of vapor intrusion sound? No, not for PHCs because very low IA concentrations overlying very low source strengths and low SG are very likely background. In addition, PHC sites constitute only 3% of the sites evaluated and may over-predict CVOC attenuation. The database shows little or no correlation between VOC concentration in soil gas and IA, and only low correlation between VOC concentration in groundwater and IA. This indicates that AFs/groundwater screening concentrations may be very poor tools for evaluation of the vapor intrusion pathway. I suspect these trends are largely due to the CVOCs because experience with VI at CVOC sites show low µg/L CVOC concentrations in groundwater that have vapor intrusion, and sites with mg/L CVOC concentrations in groundwater but no vapor intrusion.
6				Is it clearly documented? Yes.
6				Are there alternative approaches that should be used or considered? Yes, remove PHCs from this document and focus on the more problematic CVOCs.
6				What might be possible impacts of any alternative methods on the report conclusions? That exterior SG sampling at PHC sites is adequate, acknowledgement that CVOCs can cause VI even at low concentrations, and that poorly characterized CVOC sites may give false or inaccurate results.
7				Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation? No, not for the PHC sites in this d-base cause some of the source and SG concentrations are so low they likely are background.
7				Is the discussion on the use of the data understandable? Yes.
7				Are there alternative approaches that may provide additional insights? Yes. I found that a line-by-line, depth-by-depth review and subjective analysis of the available PHC data were necessary for me to characterize data anomalies and understand subsurface vapor occurrence and attenuation relative to source strength.
General	Cover			Add “for Chlorinated Hydrocarbons” to the end of the title
General	1.0			Add Purpose and Objectives before Introduction
	1.0			Add the word investigation to 3rd sentence, 1st paragraph: Since 2002, EPA has been collecting additional observations from vapor intrusion investigation sites to improve our knowledge and understanding of vapor intrusion, and in particular, the attenuation of vapors between the subsurface and indoor air.

Table A-1. Robin Davis—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
	1.0			Last sentence 1st paragraph: This report provides updated information about the database (i.e., design, structure, and content) and some example analyses using data from the database that could be useful for regulators, responsible parties, and others assessing and managing vapor intrusion investigation programs. Comment: This sentence above implies that VI occurs at all sites. Specify that the sites are investigated for VI, but not all sites have VI.
	4.0			1st paragraph: PHCs should be excluded from this data analysis because: 1) There are very little data for PHCs (only 3%, total 9 sites. 5 MADEP sites do not have usable for this analysis, and the BP Paulsboro site is poor-quality data); 2) For PHC sites, exterior SG sampling, rather than sub-slab is proven to representative and protective. There are no field data that suggest oxygen is depleted beneath buildings (or paved surfaces) and vapors accumulate there unless the source is directly below the building. For example, the Paulsboro site only shows a "vapor cloud" because the basement sits directly above the source and within the contaminated zone; 3) PHCs behave very differently than CVOCs. PHCs are well-known to biodegrade and attenuate (EPA 1999) and cause VI only at high concentrations in close proximity to building foundations Davis 2009, McHugh et al 2009), whereas CVOCs may cause VI even at very low source concentrations, and; 4) For these good reasons, EPA (2002) recommends evaluating PHC separate for CVOCs.
	4.0			Table 2: Mount Holly should indicate sub-slab and SG
	5.0	5.4		1st paragraph: Adequate site characterization is a basic and fundamental necessity for investigating any exposure pathway. This document implies that EPA is willing to use poorly characterized sites in their data analysis, and that is unacceptable.
	5.0	5.4		2nd paragraph: Adequate site characterization is a basic and fundamental necessity for investigating any exposure pathway. This document implies that EPA is willing to use poorly characterized sites in their data analysis, and that is unacceptable.
	5.0	5.4		3rd paragraph: Comment 1: 1 order of magnitude is insignificant especially at low concentrations and considering the range of background concentrations. Comment 2: Said clearly, source concentrations and groundwater elevation seasonal fluctuations are the biggest causes of variability.
	5.0	5.4		4th paragraph: Comment: 1 order of magnitude is not "considerable" especially at low concentrations and considering the range of background concentrations.

Table A-1. Robin Davis—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
	5.0	5.4		5th paragraph last sentence: This statement is highly objectionable because: 1) some of the sites in Figure 1 have very low concentrations that may be influenced by background, thereby making such a statement falsely alarmist; 2) The figure includes only a very few PHC sites: (a) all data points for the PHC sites fall below the line, and exterior sampling was representative, (b) about half or more of those PHC sites, source and SG concentrations were very low, near or at background. Those data points do not belong on the graph, and; (c) Abundant data exists for PHC sites where interior and exterior multi-depth and sub-slab SG can be evaluated. These data indicate that exterior sampling is representative of contaminant distribution. Please remove PHC data from this document.
	5.0	5.4		6th paragraph 1st sentence: Delete "changing climate conditions" and insert "seasonal fluctuations of groundwater elevation."
	5.0	5.5		2nd paragraph 6th sentence: Insert the word "investigation:" For other chemicals-such as 1,1-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; and trichloroethylene-a substantial proportion of the indoor air concentrations at the vapor intrusion investigation sites in EPA's database tend to be higher than background.
	5.0	5.5		Tables 4 and 5 µg/m3 ??? (units are absent)
	5.0	5.5		5th paragraph 2nd sentence: Insert the phrase "and biodegradation of PHCs." Because of the attenuation and dilution, and biodegradation of PHCs that occur as vapors migrate from the subsurface upwards through soil and into a ventilated building, indoor air concentrations resulting from vapor intrusion are expected to be considerably less than the subsurface concentration.
	5.0	5.5		7th paragraph 3rd sentence: Comment: A single pair is not enough data to draw or base any conclusion.
	6.0	6.2		1st paragraph, 1st sentence: Comment: According to page 12, exterior samples may not be representative. This calls into question the data quality used in this document's analyses.
	7.0			In reference to the first sentence, Is this an objective?
	7.0			1st paragraph: Comment: There is not enough PHC data to any kind of statistical analysis and should therefore be excluded from this document entirely.
	7.0			Paragraph 3, 1st sentence: Is this another objective?

Table A-2. Philip Dixon—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
General				I commend the authors for compiling a detailed database and making it available for the risk assessment community. My review focuses on the statistical aspects of the document, primarily the estimation of attenuation factors. The analysis of attenuation factors is characterized as a 'preliminary analysis' in both the document title and introduction. Hence, my comments are primarily suggestions for a more thorough analysis. My comments are organized by the general and specific questions asked in the charge, followed by a few detailed comments on the text.
1				Is the document clear with respect to objectives and purpose? Yes
1				Is there an adequate problem statement? Yes
1				Are the stated objectives and purpose met? Yes
2				Very well.
3				No, but this is not my area of expertise.
4				Yes to both questions.
5				Yes, the use of the Kaplan-Meier estimator is very reasonable. The partial exclusion of values < reporting limit is appropriate, because the data are paired. If the source concentration is small and poorly estimated (and hence reported as < reporting limit) that observation provides limit information about an attenuation factor. Retaining these observations in the data base, but omitting them from attenuation factor calculations, is a very appropriate strategy.
6				Was the potential for indoor sources of background VOCs appropriately considered when interpreting results? Yes, the document includes an extensive discussion of the issues associated with indoor sources of background VOCs.
6				Is the method used for screening and filtering data to identify real instances of vapor intrusion sound? It is difficult to estimate attenuation factors (AF) when there is a non-zero background concentration unrelated to the subsurface source. The approach used in this document, i.e., subsetting the data, is a reasonable way to reduce bias. The comparison of AF among chemicals from the same sample is a very nice way to identify specific problems. Both methods are attempts to reduce the influence of the background concentration. Other methods to eliminate the bias (discussed in alternative approaches section) may be better.
6				Is it clearly documented? Yes.
6				Are there alternative approaches that should be used or considered? There are two weaknesses with the current approach

Table A-2. Philip Dixon—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
6				1) After subsetting the data, the background concentration is ignored in the calculations. If there is a non-zero background concentration, the calculated empirical attenuation factor has to overestimate the true attenuation factor. Equation 2 is a nice demonstration of this. The bias may be judged (on practical grounds) to be small relative to the uncertainty and variability in AF, but the calculated values are still overestimates. The goal of the subsetting is to reduce the bias. Why not try to eliminate the bias by actually estimating the quantity defined by equation 1? In other words, why not estimate AFIA using (CIA—CIA,BKND) / CSOURCE. The tradeoff is that such an estimate will be more variable (and may be negative) because of the uncertainty in CIA,BKND.
6				Since you do not (or do not consistently) have site-specific estimates of CIA,BKND, you will need to use values from the distribution in the companion document. If you are concerned about the choice of CIA,BKND to use in the calculation, you can either do an error analysis or a quick sensitivity analysis. The error analysis would compare the variance of CIA / CSOURCE to the variance of CIA,BKND / CSOURCE. The sensitivity analysis would compute adjusted attenuation factors using different values for CIA,BKND, e.g., the 10th percentile, the 50th percentile, and the 90th percentile. My guess is that the choice of CIA,BKND will have little impact for data set 2 [2008], which would validates the claim that the estimated AF's in data set 2 [2008] are less influenced by background values.
6				2) You are computing distributions of attenuation factors for individual paired samples. This is appropriate if the data are a simple random sample from the population of interest. However, the data comes from a cluster sample. Sites are the clusters, houses within sites are the subsamples. Some data sets are a three stage cluster sample, with the additional layer of times (seasons) within houses. You indicate that you expect site-specific variation in attenuation factors. Analysis of cluster samples is based on calculating appropriate values for each cluster, then averaging across clusters. That means calculating a site-specific overall attenuation factor for each site, then looking at the distribution of AF across sites. Such an approach seems to be throwing away data, but this is often an illusion.
6				My guess is that variability in the individual observations is much higher than the variability in the site means, e.g., because of spatial, temporal, measurement, and analytic variability. Averaging to site means reduces the contribution of these unwanted sources of variability and is focuses attention on the variation that seems to be most important: that between sites.
6				There is a technical detail to be resolved: how to calculate the site-specific attenuation factor. One could averaging individual estimates within a site or calculate mean CIA and CSOURCE for each site then compute the attenuation factor from the means. These correspond to an unweighted and ratio estimator of the site-specific AF. Consult with a survey statistician for advice on the appropriate choice for these data.
6				What might be possible impacts of any alternative methods on the report conclusions? Reduced bias, more appropriate assessment of variability, focusing attention on the variation that matters.

Table A-2. Philip Dixon—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
7				Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation?
7				Is this analysis included in the document? I didn't see it. All I see are scatter plots and cumulative percentile plots for entire data sets, except that points are coded by < or > rl in the scatter plots for data set 1. This coding does not represent the potentially interesting variation between studies, sites, or chemicals. The warning at the bottom of the first paragraph on p 36 is very appropriate. However, there is a lot more you can do to understand the variability between sites (detailed below). If do this, you will have an estimate of the uncertainty associated with extrapolating to new sites (so long as they reasonably come from same population as the studied sites).
7				Is the discussion on the use of the data understandable? I suspect most users will be interested only in the median AF, and perhaps in selected quantiles, i.e., parts of the tables associated with e.g., figure 6.
7				Are there alternative approaches that may provide additional insights? a) You say (p 17, bottom) that you have an error propagation analysis that quantifies the consequences of measurement error. This is quite large. This analysis should be more prominent and it would be useful to see the details. Some of the scatter in e.g., figure 4 is a consequence of this measurement error. Knowing the size of the measurement error (large or small) will very much help interpret the scatter plots (e.g., figure 4). b) Why not quantify the variability between sites and / or between chemicals by doing a variance components analysis, probably on the log AF scale. If you have information about the measurement or analytic variance, that can be incorporated into the variance components analysis. This may require some hand calculation, if you have an estimate of the measurement variance instead of raw data. However, the calculations should be straightforward for a someone familiar with variance components analysis.
			1	Equation 1: This equation is very clear. The next paragraph about empirical attenuation factors is not focused. I thought the point of the paragraph below equ 1 was that you were going to calculate the quantity defined in equ 1 from data (that's what empirical means). No! your use of empirical AF defines a very different quantity CIA / CSOURCE. You need to define this new quantity prominently. The consequence of the fuzzy definition here is that all the discussion of bias due to background in section 5.5 is very confusing, until you realize that you are not talking about the quantity defined so prominently in equ 1.
			2	Footnote 2. Delete, since it's not true in this version.
			3	Citation to an excel spreadsheet in Helsel 2005a. Is this the correct citation? I don't see any spreadsheet in my copy of Helsel 2005.
			24	Soil-gas to indoor air AF. The correlation between soil gas and indoor air values seems very close to 0. If there is little (or no) association between the source and indoor air values, is it appropriate to calculate an AF? I don't think so.

Table A-2. Philip Dixon—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
			28	Description of figure 11a as showing the 2002 and 2008 distributions as 'very similar'. Isn't that a bit overstated? Some of the upper percentiles differ by a factor of 10.
			36	2nd paragraph, phrase about 'more reliable statistics'. What is a more reliable statistic? More precise perhaps. If bias equally affects the 2002 and 2008 values, then 2008 is not more accurate.

Table A-3. James Harrington—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
General				This report should include a link to the actual database. Appendices are included that describe the data dictionary for the database. Without being able to access the database, the appendices have no value. While the report provides some summary information about what is included in the database, this information cannot be used to compare a site(s) in the study to one that a reader might be familiar with.
General				The report should provide guidance on how the attenuation information can be used. The data summary shows that the attenuation factors vary significantly but does not provide any guidance on how to apply it for new sites. By taking a conservative approach, it would seem that soil gas information could be used to predict indoor air.
	7.0			The summary and conclusions section should underscore the fact that this data includes contamination from indoor sources which must be factored into decisions regarding whether mitigation is needed. The summary and conclusions section should discuss the fact that calculated attenuation factors greater than one are indicative of indoor sources and that it is impossible for levels higher than subslab or crawlspace to be attributed solely to vapor intrusion.
	5.0	5.4		Section 5.4 should include more information on spatial and temporal variability. While it seems to be an accepted fact by most practitioners, the text should include more supporting information. Further, the report should discuss how spatial and temporal variability impacts the conclusions of the report.
	5.0	5.4		The largest issue is the treatment of non-detects but is relegated to a couple of paragraphs in Section 5.2. I have no disagreement with the choice but there needs to be more discussion of what the Kaplan—Meyer method is and why the substitution method is problematic.
General				This document needs to underscore that the database is primarily information of sites with chlorinated compounds (not petroleum compounds) and the attenuation of petroleum is significantly different because of biodegradation.
	5.0	5.5		Units are missing on Tables 4 and 5

Table A-4. Mart Oostrom—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
General				This is a well written document. The authors have compiled an impressive and useful database. The various data screening steps are clearly explained. Important data and statistics for the various types of attenuation coefficients are summarized in Figs. 4–15.
1				Is the document clear with respect to objectives and purpose? Is there an adequate problem statement? Yes, the authors provide the objectives of the report in the final paragraph of Section 1.
1				Are the stated objectives and purpose met? By describing the development of the data base, including providing an evaluation of the attenuation coefficients, the objectives were met.
2				The strengths and limitations have not been explicitly listed. However, they are apparent when reading the report.
3				It appears that the authors have taken into consideration all know data sets.
4				The methods are well described. The discussion is clear except for some issues discussed in the Additional Comment section below. The discussion culmination into Figs. 4–15 is brief but to the point. It would be, in my opinion, very useful to expand this section by providing information for the 4 or 5 most common chemicals. Repeating Figs. 4-6 for a selected number of pertinent chemicals would be illustrative to obtain knowledge about individual attenuation behavior.
5				Yes, the discussion is clear and authors have used acceptable methods.
6				Was the potential for indoor sources of background VOCs appropriately considered when interpreting results? The discussion on the influence of background concentrations on attenuation coefficient concentration computations is clear.
6				Is the method used for screening and filtering data to identify real instances of vapor intrusion sound? Is it clearly documented? The methods for the various screening options are well described. It's not clear how the authors justify using a cutoff of 1 and not a lower value for the attenuation factors (see comment below). It would also be helpful to show the readers some numerical examples explaining the various screening processes.
7				Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation? The presented methods are adequate. However, the authors should provide an explanation what the implications are of the info presented in Figs. 4–15. The attenuation factors tend to have a huge range so it appears that almost any value found at a site may be considered within the range of possibilities. In light of that, how should data from a new site [be] evaluated?
	1.0		2	The authors introduce the term "empirical attenuation factor" when discussing the effects of potential indoor sources. The authors should define that term and should consider introducing Eq. 2 at this point in the text. It's not clear to my why that attenuation factor is called "empirical" as the attenuation factor in Eq. 1 is also of empirical nature. Maybe using "apparent" instead of "empirical" for attenuation coefficients affected by indoor sources may be considered.

Table A-4. Mart Oostrom—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
	2.0		2	The footnote state that tables are figures are provided at the end of the report. This is not the case in the draft I received where all tables and figures are in the text.
	4.0		4	The authors need to be careful with the term chlorinated hydrocarbons with regard to carbon tetrachloride. Carbon tetrachloride is not a hydrocarbon.
	5.0	5.1	8	The concurrency for paired groundwater and indoor air data is given as "a few weeks." This seems to be somewhat loose compared to the 48 hours for the other data pairs. What time period was actually used in this data base?
	5.0	5.1	8	Table 3 is introduced and the Data Quality Screen data are explained. The other screens are not explained yet. It is suggested that the authors make a statement at the end of Section 5.1 to explain when (in what section) the other 3 screened data would be introduced. Table 3 is rather important and should be referred to several times in the report.
	5.0	5.2	10	It would be illustrative for readers to provide an example of a few data pairs that were screened out when developing the Subsurface Screen Data from the Data Quality Screen Data. The authors provide good decision descriptions but a few numeric examples will go a long way explaining why some data pairs were excluded.
	5.0	5.3	11	Final paragraph Section 5.3. The paragraph seems to be out of place. So far the readers have not seen any results so how can they "note" what the authors are saying? It's better to state these observations in a later section.
	5.0	5.4	11	The authors discuss the potential of introducing high and low bias in concentration. An example of both cases should be given to clarify discussion with readers.
	5.0	5.4	12	The authors discuss the several sources of variability. It is not clear whether some data pairs were excluded from consideration because of unexpectedly high or low bias. Is there a way to know whether certain attenuation factors are actually biased?
	5.0	5.5	15	I don't understand the sentence "Vapor intrusion …. due to vapor intrusion." Why do the background concentrations in any given setting have to be equivalent or higher than the vapor intrusions concentrations in order to get a high bias? I would say that anytime there is a background concentration > 0, there will be a bias. For equivalent concentrations or higher, the bias would be 50% or more.
	5.0	5.5	16	Consider introducing Eq. 2 in the Introduction, right after Eq. 1.
	5.0	5.5	17	First paragraph. It is not clear how the data being flagged and excluded due to background influenced are related to Table 3. A numerical example explaining the exclusion would be helpful.
	5.0	5.5	17	Second paragraph. Same for the data being excluded in this paragraph. How does this relate to the data sets in Table 3. Again, a numerical example explaining the exclusion would be helpful.

Table A-4. Mart Oostrom—Comment Matrix for Vapor Intrusion Database

Charge Question	Guidance Section	Guidance Sub-Section	Page No.	Comment / Recommendations
	5.0	5.5	18	Johnson (2002) suggested and upper limit of 0.05 for subslab-to-indoor-air attenuation factors. The authors also state that vapor intrusion attenuation factors are expected to be significantly less than 1. However, at the end of the paragraph it is stated that "For these reasons, … further analysis." Given the suggestion by Johnson (2002) and other statements in this report claiming that the attenuation factors should be << 1, how do the authors justify a cut-off at 1?
	5.0	5.5	18	Third paragraph. This seems like advice for future sampling? Have the current data sets been modified based on the mentioned sampling issues?
	6.0		19	A lot of the previously mentioned confusion on how data exclusions are related to Table 3 can be taken away by using some of the text on page 19 earlier in this section.
	6.0	6.1	19	It's not clear where the Henry's constants are listed. I could not find them in the Appendices.
	6.0	6.1	22	Figure 5: Consider combining all 4 lines into one figure. That way, the data presentation is more consistent with Figs. 8 and 10 that do have lines from Data Set 1 and 2 in one figure.
	6.0	6.2		Figures 8 and 9: It's not clear why values > 1 are allowed in these figures. Based on the text on Page 17, factors equal to or greater were excluded. I'm missing something here but I'm not sure what.
	6.0	6.4		Figures 13 and 14: It's not clear why values > 1 are allowed in these figures. Based on the text on Page 17, factors equal to or greater were excluded. I'm missing something here but I'm not sure what.
	6.0			Figure 4 and others: Explain what alpha is.
	7.0		36	First paragraph. A short description on how this data base might be useful would be useful.
	7.0		36	Second paragraph. It's not clear why some data from Table A-1 are repeated here. A simple reference to the Table should be sufficient. In general, this paragraph seems to be a combination of a data summary followed by some conclusions. Separating this paragraph after "….was available in 2002," would be helpful to help the reader.
	7.0		38	Final paragraph. The major implications of the variability in attenuation factors should be listed.

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Attachment A-2

Peer Review Comments by Commenter

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Robin Davis

July 18, 2009

Robin Davis Comments on EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors

Thank you for this opportunity to review. I have addressed the General and Specific Charge Questions below. I have also typed comments in the document itself (separate document). All of my comments are shown in purple-bold-Arial font in both documents.

Robin V. Davis, P.G., Environmental Scientist, Project Manager
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Peer Review Charge for:

U.S. Environmental Protection Agency (EPA). 2008. *U.S. EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors.* EPAxxx-x-xx-xxx. Office of Solid Waste and Emergency Response. March 4 (review draft).

General Charge Questions

1. **Is the document clear with respect to objectives and purpose?**

   No. The document states no purpose and objectives, and is unclear in statements made in the document that might even allude to purpose and objectives. There should be a section that clearly states the purpose and objective, otherwise, practitioners won't know why they would be reading it. There are only allusions of any purpose or objective in section 7.0, Summary and Conclusions," page 36, paragraph 1 where there is discussion helping environmental professional understand the VI pathway and attenuation from subsurface to indoor air. Paragraph 3 alludes to an objective: understanding influences of contaminant concentrations in background air. I agree that this data analysis may be useful for chlorinated VOCs (CVOCs), but the data analyses are not at all representative or useful for petroleum hydrocarbon (PHCs).

   EPA OSWER's Draft VI Guide (Nov. 2002) wisely cautioned against its use at PHC sites because PHC is known to biodegrade. The Guide in fact recommended that PHC be studied separately (which is being done at a much greater rate than for CVOCs). EPA OSWER should use this current opportunity to issue a similar but stronger and more clearly and definitively articulated statement that this document does not have sufficient or meaningful PHC data to draw any statistical conclusion. I strongly advise that PHC be removed from this document. I have studied the PHC data in this EPA d-base and from hundreds of other PHC sites. I have evaluated these data subjectively and know and understand anomalies, I know, for example that the PHC data used in the EPA d-base and shown in Figure 1 all fall well below the line in Figure 1. I also know that for some of the sub-slab and exterior SG exhibit very low benzene SG concentrations (e.g., Stafford Bldgs 3, 22, 14 and 18, and Mt. Holly 91 and 103 Hulme St.). Enough high-quality PHC data have been collected to show that exterior SG sampling is representative and avoids unnecessary, costly and intrusive sub-slab sampling. I therefore cannot accept any suggestion that exterior soil gas (SG) sampling for PHC is not representative and that every site would require sub-slab SG sampling.

Is there an adequate problem statement?

No. There is no problem statement at all. My suggestion for one would include discussion of the following: 1) CVOCs are in many if not most consumer products and constitute the majority of VI sites); 2) VI from subsurface sources can be difficult to determine because of influence by contaminants in background air, especially at low levels in the subsurface and especially for CVOCs; 3) CVOCs, which are not readily degradable and have toxic by-products have been evaluated for VI along with PHC, which can influence the results of data analysis because: PHC is biodegraded to innocuous by-products and causes VI only under extreme conditions (very high concentrations in close proximity to building foundations); 4) More data are needed to better understand CVOC VI, 5) Exterior SG sampling for CVOCs may not be representative and; 6) While PHC sites are usually very well-characterized, CVOC sites are often not because, since CVOCs are not very degradable, they often form large plumes widespread in extent.

Are the stated objectives and purpose met?

No because there are no stated purpose and objectives. This is troubling because it shows that this document is not only not useful, it erroneously implies that PHCs behave and intrude enclosed spaces in the same way that CVOCs do.

2. Are the strengths and limitations of the study clearly laid out in the documentation?

No. Mention of strengths and limitations is dispersed throughout the document, which makes reading this document tedious and leaving one to question its value. There is little mention of substantial limitation until Conclusion, sentence 4. Discussion of strengths and limitations needs its own section and should include discussion of: Strengths: 1) Although limited, the data show that CVOCs constitute majority of VI sites; 2) Knowledge that PHC biodegrades (EPA 1999) and its associated vapors rarely intrude buildings unless high source strengths lie within about 5 feet beneath a building (Davis,2009; McHugh, et al, 2009 in press). Limitations: 1) The database clearly includes background influences and <RL or very low SG concentrations; 2) contains too small a data set of PHC (only 3%) to warrant statistical analysis much less inclusion in this OSWER document. In general, the current data are difficult to evaluate for VI investigations because of background influence and comparison to very low concentrations; 3) Site characterization at CVOC sites is often not thorough, whereas PHC sites are well-characterized because the plumes are smaller due to biodegradation.

3. **Are you aware of any additional information that would significantly reduce key uncertainties, change the overall findings of, or significantly improve the document? For example, are there other good studies or sources on vapor intrusion attenuation data that you are aware of that were not included?**

   Yes. There are abundant subsurface-only PHC data that are not included in the EPA database that show rapid biodegradation and attenuation by many orders of magnitude, and that PHC sites only cause VI when source concentrations are very high and in close proximity to building foundations.

   The document would be greatly improved by removing PHC from the analyses because unnecessary alarm to property occupants would be avoided and expenditures of limited financial resources would be greatly reduced. There are many good studies on PHC sites that have high-quality data, sites are very well-characterized, and subsurface SG attenuation is very strong and vapors are often completely attenuated within a few feet above even very strong sources.

Specific Charge Questions

4. **Are the methods used to collect, compile, document, and ensure the quality of the vapor intrusion data adequate and were the methods used appropriately? Is the discussion understandable?**

   While the discussion is understandable, the application is objectionable because: 1) the document admits that data quality at some sites is low, sites may not be well-characterized, and source strengths beneath buildings may not be known. Poor site characterization is often the case for CVOCs but not for PHCs. I think the document should exclude data from sites that are not well- characterized and all data from PHC sites. Also, I entirely disagree that the small PHC data set can be used to make any analysis at all about PHC, and; 2) On page 12 it is stated that exterior SG may be not be representative (which is not supportable by this document and a point on which I entirely disagree), then on page 24, AFs are calculated using those exterior points.

5. **Were measurements below reporting limits appropriately treated and considered in the data analysis?**

   Probably OK for CVOCs but not for PHCs because all of the PHC data show biodegradation beneath and exterior to buildings if sufficient clean overlying soil exists. Only Stafford Bldg 73 w/basement has VI not because of a preferential anoxic zone due to the slab but because of the close proximity of the basement to the source and insufficient thickness of clean overlying soil.

6. **Was the potential for indoor sources of background VOCs appropriately considered when interpreting results?**

   No. On page 13, the reference to Table 5 shows that for most chemicals—including tetrachloroethylene; 1,1,1-trichloroethane; and the petroleum hydrocarbons—the indoor air concentrations at the vapor intrusion sites in the database are roughly equivalent in range to the background indoor air concentrations in Table 4. This seems to be saying that, based on the limited data in the database, there is no evidence that petroleum hydrocarbons are causing vapor intrusion. Is the method used for screening and filtering data to identify real instances of vapor intrusion sound? No, not for PHCs because very low IA concentrations overlying very low source strengths and low SG are very likely background. In addition, PHC sites constitute only 3% of the sites evaluated and may over-predict CVOC attenuation. The database shows little or no correlation between VOC concentration in soil gas and IA, and only low correlation between VOC concentration in groundwater and IA. This indicates that AFs/groundwater screening concentrations may be very poor tools for evaluation of the vapor intrusion pathway. I suspect these trends are largely due to the CVOCs because experience with VI at CVOC sites show low µg/L CVOC concentrations in groundwater that have vapor intrusion, and sites with mg/L CVOC concentrations in groundwater but no vapor intrusion. Is it clearly documented? Yes. Are there alternative approaches that should be used or considered? Yes, remove PHCs from this document and focus on the more problematic CVOCs. What might be possible impacts of any alternative methods on the report conclusions? That exterior SG sampling at PHC sites is adequate, acknowledgement that CVOCs can cause VI even at low concentrations, and that poorly characterized CVOC sites may give false or inaccurate results.

7. **Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation?**

   No, not for the PHC sites in this d-base cause some of the source and SG concentrations are so low they likely are background. Is the discussion on the use of the data understandable? Yes. Are there alternative approaches that may provide additional insights? Yes. I found that a line-by-line, depth-by-depth review and subjective analysis of the available PHC data were necessary for me to characterize data anomalies and understand subsurface vapor occurrence and attenuation relative to source strength.

Philip Dixon

Review of U.S. Environmental Protection Agency (EPA). 2008. *U.S. EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors.* EPAxxx-x- xx-xxx. Office of Solid Waste and Emergency Response. March 4 (review draft).

I commend the authors for compiling a detailed database and making it available for the risk assessment community. My review focuses on the statistical aspects of the document, primarily the estimation of attenuation factors. The analysis of attenuation factors is characterized as a 'preliminary analysis' in both the document title and introduction. Hence, my comments are primarily suggestions for a more thorough analysis. My comments are organized by the general and specific questions asked in the charge, followed by a few detailed comments on the text.

General Charge Questions

1. **Is the document clear with respect to objectives and purpose?**
   Yes

   Is there an adequate problem statement?
   Yes

   Are the stated objectives and purpose met?
   Yes

2. **Are the strengths and limitations of the study clearly laid out in the documentation?**
   Very well.

3. **Are you aware of any additional information that would significantly reduce key uncertainties, change the overall findings of, or significantly improve the document? For example, are there other good studies or sources on vapor intrusion attenuation data that you are aware of that were not included?**

   No, but this is not my area of expertise.

Specific Charge Questions

4. **Are the methods used to collect, compile, document, and ensure the quality of the vapor intrusion data adequate and were the methods used appropriately? Yes.**

   Is the discussion understandable? Yes

5. **Were measurements below reporting limits appropriately treated and considered in the data analysis?**

Yes, the use of the Kaplan-Meier estimator is very reasonable. The partial exclusion of values < reporting limit is appropriate, because the data are paired. If the source concentration is small and poorly estimated (and hence reported as < reporting limit) that observation provides limit information about an attenuation factor. Retaining these observations in the data base, but omitting them from attenuation factor calculations, is a very appropriate strategy.

6. **Was the potential for indoor sources of background VOCs appropriately considered when interpreting results?**

Yes, the document includes an extensive discussion of the issues associated with indoor sources of background VOCs.

Is the method used for screening and filtering data to identify real instances of vapor intrusion sound?

It is difficult to estimate attenuation factors (AF) when there is a non-zero background concentration unrelated to the subsurface source. The approach used in this document, i.e. subsetting the data, is a reasonable way to reduce bias. The comparison of AF among chemicals from the same sample is a very nice way to identify specific problems. Both methods are attempts to reduce the influence of the background concentration. Other methods to eliminate the bias (discussed in alternative approaches section) may be better.

Is it clearly documented?

Yes

Are there alternative approaches that should be used or considered?

There are two weaknesses with the current approach: 1) After subsetting the data, the background concentration is ignored in the calculations. If there is a non-zero background concentration, the calculated empirical attenuation factor has to overestimate the true attenuation factor. Equation 2 is a nice demonstration of this. The bias may be judged (on practical grounds) to be small relative to the uncertainty and variability in AF, but the calculated values are still overestimates. The goal of the subsetting is to reduce the bias. Why not try to eliminate the bias by actually estimating the quantity defined by equation 1? In other words, why not estimate AF_{IA} using $(C_{IA} - C_{IA,BKND}) / C_{SOURCE}$. The tradeoff is that such an estimate will be more variable (and may be negative) because of the uncertainty in $C_{IA,BKND.}$

Since you do not (or do not consistently) have site-specific estimates of $C_{IA,BKND}$, you will need to use values from the distribution in the companion document. If you are concerned about the choice of $C_{IA,BKND}$ to use in the calculation, you can either do an error analysis or a quick sensitivity analysis. The error analysis would compare the variance of C_{IA} / C_{SOURCE} to the variance of $C_{IA,BKND} / C_{SOURCE}$. The sensitivity analysis would compute adjusted attenuation factors using different values for $C_{IA,BKND}$, e.g. the 10th percentile, the 50th percentile, and the 90th percentile. My guess is that the choice of $C_{IA,BKND}$ will have little impact for data set 2 [2008], which would validates the claim that the estimated AF's in data set 2 [2008] are less influenced by background values.

2) You are computing distributions of attenuation factors for individual paired samples. This is appropriate if the data are a simple random sample from the population of interest. However, the data comes from a cluster sample. Sites are the clusters, houses within sites are the subsamples. Some data sets are a three stage cluster sample, with the additional layer of times (seasons) within houses. Analysis of cluster samples is based on calculating appropriate values for each cluster, then averaging across clusters. That means calculating a site-specific overall attenuation factor for each site, then looking at the distribution of AF across sites. Such an approach seems to be throwing away data, but this is often an illusion. My guess is that variability in the individual observations is much higher than the variability in the site means, e.g. because of spatial, temporal, measurement, and analytic variability. Averaging to site means reduces the contribution of these unwanted sources of variability and is focuses attention on the variation that seems to be most important: that between sites.

You indicate that you expect site-specific variation in attenuation factors.

There is a technical detail to be resolved: how to calculate the site-specific attenuation factor. One could averaging individual estimates within a site or calculate mean C_{IA} and C_{SOURCE} for each site then compute the attenuation factor from the means. These correspond to an unweighted and ratio estimator of the site-specific AF. Consult with a survey statistician for advice on the appropriate choice for these data.

What might be possible impacts of any alternative methods on the report conclusions?

Reduced bias, more appropriate assessment of variability, focusing attention on the variation that matters.

7. Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation?

Is this analysis included in the document? I didn't see it. All I see are scatter plots and cumulative percentile plots for entire data sets, except that points are coded by < or > rl in the scatter plots for data set 1. This coding does not represent the potentially interesting variation between studies, sites, or chemicals.

The warning at the bottom of the first paragraph on p 36 is very appropriate. However, there is a lot more you can do to understand the variability between sites (detailed below). If do this, you will have an estimate of the uncertainty associated with extrapolating to new sites (so long as they reasonably come from same population as the studied sites).

Is the discussion on the use of the data understandable?

I suspect most users will be interested only in the median AF, and perhaps in selected quantiles, i.e. parts of the tables associated with e.g. figure 6.

Are there alternative approaches that may provide additional insights?

a) You say (p 17, bottom) that you have an error propagation analysis that quantifies the consequences of measurement error. This is quite large. This analysis should be more prominent and it would be useful to see the details. Some of the scatter in e.g. figure 4 is a consequence of this measurement error. Knowing the size of the measurement error (large or small) will very much help interpret the scatter plots (e.g figure 4).

b) Why not quantify the variability between sites and / or between chemicals by doing a variance components analysis, probably on the log AF scale. If you have information about the measurement or analytic variance, that can be incorporated into the variance components analysis. This may require some hand calculation, if you have an estimate of the measurement variance instead of raw data. However, the calculations should be straightforward for a someone familiar with variance components analysis.

Detailed comments on the text:

p 1, equ. 1. This equation is very clear. The next paragraph about empirical attenuation factors is not focused. I thought the point of the paragraph below equ 1 was that you were going to calculate the quantity defined in equ 1 from data (that's what empirical means). No! your use of empirical AF defines a very different quantity C_{IA} / C_{SOURCE}. You need to define this new quantity prominently. The consequence of the fuzzy definition here is that all the discussion of bias due to background in section 5.5 is very confusing, until you realize that you are not talking about the quantity defined so prominently in equ 1.

p 2. footnote 2. Delete, since it's not true in this version.

p 3, citation to an excel spreadsheet in Helsel 2005a. Is this the correct citation? I don't see any spreadsheet in my copy of Helsel 2005.

p 24, soil-gas to indoor air AF. The correlation between soil gas and indoor air values seems very close to 0. If there is little (or no) association between the source and indoor air values, is it appropriate to calculate an AF? I don't think so.

p 28, description of figure 11a as showing the 2002 and 2008 distributions as 'very similar'. Isn't that a bit overstated? Some of the upper percentiles differ by a factor of 10.

p 36, 2nd paragraph, phrase about 'more reliable statistics'. What is a more reliable statistic? More precise perhaps. If bias equally affects the 2002 and 2008 values, then 2008 is not more accurate.

James Harrington

Comments on "USEPA Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors"

1. This report should include a link to the actual database. Appendices are included that describe the data dictionary for the database. Without being able to access the database, the appendices have no value. While the report provides some summary information about what is included in the database, this information can not be used to compare a site(s) in the study to one that a reader might be familiar with.

2. The report should provide guidance on how the attenuation information can be used. The data summary shows that the attenuation factors vary significantly but does not provide any guidance on how to apply it for new sites. By taking a conservative approach, it would seem that soil gas information could be used to predict indoor air.

3. The summary and conclusions section should underscore the fact that this data includes contamination from indoor sources which must be factored into decisions regarding whether mitigation is needed.

4. The summary and conclusions section should discuss the fact that calculated attenuation factors greater than one are indicative of indoor sources and that it is impossible for levels higher than subslab or crawlspace to be attributed solely to vapor intrusion.

5. Section 5.4 should include more information on spacial and temporal variability. While it seems to be an accepted fact by most practioners, the text should include more supporting information. Further, the report should discuss how spacial and temporal variability impacts the conclusions of the report.

6. The largest issue is the treatment of non-detects but is relegated to a couple of paragraphs in Section 5.2. I have no disagreement with the choice but there needs to be more discussion of what the Kaplan - Meyer method is and why the substitution method is problematic.

7. This document needs to underscore that the database is primarily information of sites with chlorinated compounds (not petroleum compounds) and the attenuation of petroleum is significantly different because of biodegradtaion.

Editorial

1. Units are missing on Tables 4 and 5.

Mart Oostrom

U.S. EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors.

Review

This is a well written document. The authors have compiled an impressive and useful database. The various data screening steps are clearly explained. Important data and statistics for the various types of attenuation coefficients are summarized in Figs. 4 – 15. Below are my answers to the Charge Questions. I've also listed several additional comments.

General Charge Questions

1. **Is the document clear with respect to objectives and purpose? Is there an adequate problem statement? Are the stated objectives and purpose met?**

   Yes, the authors provide the objectives of the report in the final paragraph of Section 1. By describing the development of the data base, including providing an evaluation of the attenuation coefficients, the objectives were met.

2. **Are the strengths and limitations of the study clearly laid out in the documentation?**

   The strengths and limitations have not been explicitly listed. However, they are apparent when reading the report.

3. **Are you aware of any additional information that would significantly reduce key uncertainties, change the overall findings of, or significantly improve the document? For example, are there other good studies or sources on vapor intrusion attenuation data that you are aware of that were not included?**

   It appears that the authors have taken into consideration all know data sets.

Specific Charge Questions

4. **Are the methods used to collect, compile, document, and ensure the quality of the vapor intrusion data adequate and were the methods used appropriately? Is the discussion understandable?**

   The methods are well described. The discussion is clear except for some issues discussed in the Additional Comment section below. The discussion culmination into Figs. 4 – 15 is brief but to the point. It would be, in my opinion, very useful to expand this section by providing information for the 4 or 5 most common chemicals. Repeating Figs. 4-6 for a selected number of pertinent chemicals would be illustrative to obtain knowledge about individual attenuation behavior.

5. Were measurements below reporting limits appropriately treated and considered in the data analysis?

Yes, the discussion is clear and authors have used acceptable methods.

6. Was the potential for indoor sources of background VOCs appropriately considered when interpreting results? Is the method used for screening and filtering data to identify real instances of vapor intrusion sound? Is it clearly documented? Are there alternative approaches that should be used or considered? What might be possible impacts of any alternative methods on the report conclusions?

The discussion on the influence of background concentrations on attenuation coefficient concentration computations is clear. The methods for the various screening options are well described. It's not clear how the authors justify using a cutoff of 1 and not a lower value for the attenuation factors (see comment below). It would also be helpful to show the readers some numerical examples explaining the various screening processes.

7. Do the methods used for presenting and comparing attenuation factors from different studies and sites provide useful information for investigating and interpreting vapor intrusion attenuation? Is the discussion on the use of the data understandable? Are there alternative approaches that may provide additional insights?

The presented methods are adequate. However, the authors should provide an explanation what the implications are of the info presented in Figs. 4 – 15. The attenuation factors tend to have a huge range so it appears that almost any value found at a site maybe considered within the range of possibilities. In light of that, how should data from a new site being evaluated.

Additional Comments

Page 2. The authors introduce the term "empirical attenuation factor" when discussing the effects of potential indoor sources. The authors should define that term and should consider introducing Eq. 2 at this point in the text. It's not clear to my why that attenuation factor is called "empirical" as the attenuation factor in Eq. 1 is also of empirical nature. Maybe using "apparent" instead of "empirical" for attenuation coefficients affected by indoor sources may be considered.

Page 2. The footnote state that tables are figures are provided at the end of the report. This is not the case in the draft I received where all tables and figures are in the text.

Page 4. The authors need to be careful with the term chlorinated hydrocarbons with regard to carbon tetrachloride. Carbon tetrachloride is not a hydrocarbon.

Page 8. The concurrency for paired groundwater and indoor air data is given as "a few weeks". This seems to be somewhat loose compared to the 48 hours for the other data pairs. What time period was actually used in this data base?

Page 8. Table 3 is introduced and the Data Quality Screen data are explained. The other screens are not explained yet. It is suggested that the authors make a statement at the end of Section 5.1 to explain when (in what section) the other 3 screened data would be introduced. Table 3 is rather important and should be referred to several times in the report.

Page 10. It would be illustrative for readers to provide an example of a few data pairs that were screened out when developing the Subsurface Screen Data from the Data Quality Screen Data. The authors provide good decision descriptions but a few numeric examples will go a long way explaining why some data pairs were excluded.

Page 11. Final paragraph Section 5.3. The paragraph seems to be out of place. So far the readers have not seen any results so how can they "note" what the authors are saying? It's better to state these observations in a later section.

Page 11. Section 5.4. The authors discuss the potential of introducing high and low bias in concentration. An example of both cases should be given to clarify discussion with readers.

Page 12. The authors discuss the several sources of variability. It is not clear whether some data pairs were excluded from consideration because of unexpectedly high or low bias. Is there a way to know whether certain attenuation factors are actually biased?

Page 13. I don't understand the sentence "Vapor intrusion …. due to vapor intrusion." Why do the background concentrations in any given setting have to be equivalent or higher than the vapor intrusions concentrations in order to get a high bias? I would say that anytime there is a background concentration > 0, there will be a bias. For equivalent concentrations or higher, the bias would be 50% or more.
Page 16. Consider introducing Eq. 2 in the Introduction, right after Eq. 1.

Page 17. First paragraph. It is not clear how the data being flagged and excluded due to background influenced are related to Table 3. A numerical example explaining the exclusion would be helpful.

Page 17. Second paragraph. Same for the data being excluded in this paragraph. How does this relate to the data sets in Table 3. Again, a numerical example explaining the exclusion would be helpful.

Page 18. Johnson (2002) suggested and upper limit of 0.05 for subslab-to-indoor-air attenuation factors. The authors also state that vapor intrusion attenuation factors are expected to be significantly less than 1. However, at the end of the paragraph it is stated that "For these reasons, … further analysis." Given the suggestion by Johnson (2002) and other statements in this report claiming that the attenuation factors should be << 1, how do the authors justify a cut- off at 1?

Page 18. Third paragraph. This seems like advice for future sampling? Have the current data sets been modified based on the mentioned sampling issues?

Page 19. A lot of the previously mentioned confusion on how data exclusions are related to Table 3 can be taken away by using some of the text on page 19 earlier in this section.

Page 19. It's not clear where the Henry's constants are listed. I could not find them in the Appendices.

Figure 5. Consider combining all 4 lines into one figure. That way, the data presentation is more consistent with Figs. 8 and 10 that do have lines from Data Set 1 and 2 in one figure.

Figures 8, 9, 13, 14. It's not clear why values > 1 are allowed in these figures. Based on the text on Page 17, factors equal to or greater were excluded. I'm missing something here but I'm not sure what.

Figure 4 and others: Explain what alpha is.

Page 36. First paragraph. A short description on how this data base might be useful would be useful.

Page 36. Second paragraph. It's not clear why some data from Table 1 are repeated here. A simple reference to the Table should be sufficient. In general, this paragraph seems to be a combination of a data summary followed by some conclusions. Separating this paragraph after "….was available in 2002", would be helpful to help the reader.

Page 38. Final paragraph. The major implications of the variability in attenuation factors should be listed.

Appendix B

Vapor Intrusion Database Structure Documentation

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EPA OSWER Vapor Intrusion Database Spreadsheet User's Guide

The box plots and statistics are calculated by running a macro that extracts the filtered

Spreadsheet Data Dictionary

Calculated or Copied Fields	Calculated or Copied Field Description
Site Name	Copy of site or facility name
ChemName	Copy of chemical name
Chem Type	CHC = chlorinated hydrocarbon; PHC = petroleum hydrocarbon
Soil Texture Code	Copy of vadose zone soil texture codes (comma separated); dominant soil type
Soil Type (VC, C or F)	VC = very coarse, C = coarse, F = fine
Building Name	Copy of name of building, local address, local identifier, etc.
Bldg Use	Copy of use of building (residential, commercial, industrial, school, etc.)
Foundation Type	Copy of type of foundation for the building (basement, crawlspace, slab-on-grade, earthen, basement-partial, etc.)
[GW] > RL? (Y,N)	Is groundwater concentration [GW] > reporting limit (RL)?
Use [GW] Source Strength Filter? (Y,N)	Apply groundwater source strength filter (Y if yes, N if no)?
USE [GW] Alpha? (Y,N)	Use groundwater-to-indoor air attenuation factor (Y if yes, N if no)?
[GW] Comment	Comment on groundwater-to-indoor air attenuation factor
[SS] > DL? (Y,N)	Is subslab concentration [SS] > reporting limit (RL)?
Use [SS] Source Strength Filter?? (Y,N)	Apply subslab source strength filter (Y if yes, N if no)?
USE [SS] Alpha? (Y,N)	Use subslab-to-indoor air attenuation factor (Y if yes, N if no)?
[SS] Comment	Comment on subslab-to-indoor air attenuation factor
[SG] > DL? (Y,N)	Is soil gas concentration [SG] > reporting limit (RL)?
Use [SG] Source Strength Filter?? (Y,N)	Apply soil gas source strength filter (Y if yes, N if no)?
USE [SG] Alpha? (Y,N)	Use soil gas-to-indoor air attenuation factor (Y if yes, N if no)?
[SG] Comment	Comment on subslab-to-indoor air attenuation factor
[CS] > DL? (Y,N)	Is crawlspace concentration [CS] > reporting limit (RL)?
Use [CS] Source Strength Filter?? (Y,N)	Apply crawlspace source strength filter (Y if yes, N if no)?
USE [CS] Alpha? (Y,N)	Use crawlspace-to-indoor air attenuation factor (Y if yes, N if no)?
[CS] Comment	Comment on crawlspace-to-indoor air attenuation factor
[IA] > DL? (Y,N)	Is indoor air concentration [IA] > reporting limit (RL)?
[IA] > Backgrnd Filter? (Y,N)	Apply indoor air source strength filter (Y if yes, N if no)?
USE [IA] Data? (Y,N)	Use indoor air data (Y if yes, N if no)?
[IA] Comment	Comment on indoor air data
Subsurface Concentration	Subsurface concentrations (groundwater, soil gas, subslab, crawlspace) used in charts
Subsurface Alpha	Attenuation factor (groundwater, soil gas, subslab, crawlspace) used in charts
Alpha Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
Alpha Nondetect Flag (Y=1,n+0)	Field used for calculating Kaplan-Meier statistics
copy of [gw] in ug/L	Copy of groundwater [gw] concentrations
GW Temp (C); Default=15C	Groundwater temperature
Predicted [gw_vapor] in ug/m3	Calculated vapor concentration in equilibrium with groundwater concentration
copy of [ss] in ug/m3	Copy of subslab concentration (all data converted to units of ug/m3)
copy of [sg] in ug/m3	Copy of soil gas concentration (all data converted to units of ug/m3)
copy of [cs] in ug/m3	Copy of crawlspace concentration (all data converted to units of ug/m3)
copy of [ia] in ug/m3	Copy of indoor air concentration (all data converted to units of ug/m3)
95th % IA_Background	95th percentile value of background indoor air concentrations

Calculated or Copied Fields	Calculated or Copied Field Description
ia/gw alpha	Groundwater-to-indoor air attenuation factor
ia/ss alpha	Subslab-to-indoor air attenuation factor
ia/sg alpha	Soil gas-to-indoor air attenuation factor
ia/cs alpha	crawlspace-to-indoor air attenuation factor
IA/GW Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/GW Non-Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/SS Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/SS Non-Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/SG Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/SG Non-Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/CS Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics
IA/CS Non-Detect Flag (Y=1,N=0)	Field used for calculating Kaplan-Meier statistics

Data Fields	Data Field Descriptions
site_id	Unique numeric ID for site
site_name	Name of site or facility
texture_Codes	Vadose zone soil texture codes (comma separated); dominant soil type
alt_desc	Alternate soil description
hydrogeologic Setting	Hydrogeologic setting of site
source Type	Type of source (dissolved groundwater, LNAPL, DNAPL, vadose zone)
building_id	Unique numeric building ID (aka, subsite)
bldg_name	Name of building, local address, local identifier, etc.
bldg_type	Physical description of building: e.g., single family residence, one-story residence, etc.
bldg_use	Use of building (residential, commercial, industrial, school, etc.)
foundation_type	Type of foundation for the building (basement, crawlspace, slab-on-grade, earthen, basement-partial, etc.)
depth_to_foundation	Depth to base of foundation (below ground surface)
depth_to_foundation_unit	Unit for foundation depth
bldg_depth_to_src_avg	Average depth to vapor source (below foundation)
bldg_depth_to_src_unit	Units of depth to source
bldg_vapor_src_type	Vapor source type (aqueous, NAPL, etc.)
confounding_factors	Background confounding factors from survey or other source (e.g., smoking, hobbies, remodeling)
bldg_comment	Building-specific comments
parameter_name	Measurement Parameter name (e.g., trichloroethene, 1,1,1-trichloroethane)
ia_location	Building name and floor (e.g., building id (basement), building name (lowest living), etc.)
ia_sample_type	Sampling method (Summa 24 hr, Tedlar grab, etc.)
ia_lab_method	Analytical method (TO-15, TO-17, etc.)
ia_date_first	First (or only) date of indoor air sampling
ia_date_last	Last date of indoor air sampling
ia_value_type	Indoor air value type (actual, mean, max)
ia_result	Indoor air result
ia_result_unit	Units of indoor air result
ia_comment	Indoor air result comment
ia_MDL_PQL_RL	Indoor air method detection limit, practical quantitation limit, or reporting limit

Data Fields	Data Field Descriptions
ia_detect_flag_yn	Must be either "Y" for detected analytes or "N" for non_detects (indoor air)
ia_result_id	unique Id for indoor air result
ss_location	Subslab sampling location
ss_date_first	First (or only) date of subslab sampling
ss_date_last	Last date of subslab sampling
ss_vert_dist	Depth of sampling probe beneath slab base
ss_vert_dist_unit	Units for subslab sampling point depth
ss_value_type	Subslab value type (actual, estimated, interpolated, mean, max)
ss_result	Subslab result
ss_result_unit	Units of subslab result
ss_comment	Subslab result comment
ss_MDL_PQL_RL	Subslab method detection limit, practical quantitation limit, or reporting limit
ss_detect_flag_yn	Must be either "Y" for detected analytes or "N" for non_detects (subslab)
ss_alpha_id	Unique Id for paired indoor air and subslab results
gw_location	Groundwater sampling location
gw_date_first	First (or only) date of groundwater samping
gw_date_last	Last date of groundwater sampling
gw_horiz_dist	Horizontal distance of groundwater sampling point (well) from building it is assigned to
gw_horiz_dist_unit	Units for horizontal distance of groundwater sampling point
gw_vert_dist	Depth of groundwater sampling point (well) below ground surface (bgs)
gw_vert_dist_unit	Units for groundwater sampling point depth
gw_value_type	Groundwater value type (actual, estimated, interpolated)
gw_result	Groundwater result
gw_result_unit	Units of groundwater result
gw_comment	Groundwater result comment
gw_MDL_PQL_RL	Groundwater method detection limit, practical quantitation limit, or reporting limit
gw_detect_flag_yn	Must be either "Y" for detected analytes or "N" for non_detects (groundwater)
gw_alpha_id	Unique Id for paired indoor air and groundwater results
sg_location	Soil gas sampling location
sg_date_first	First (or only) date of soil gas samping
sg_date_last	Last date of soil gas sampling
sg_horiz_dist	Horizontal distance of soil gas sampling point (probe) from building it is assigned to
sg_horiz_dist_unit	Units for horizontal distance of soil gas sampling point
sg_vert_dist	Depth of soil gas sampling point (probe) below ground surface (bgs)
sg_vert_dist_unit	Units for soil gas sampling point depth
sg_value_type	Soil gas value type (actual, estimated, interpolated, mean, max)
sg_result	Soil gas result
sg_result_unit	Units of soil gas result
sg_comment	Soil gas result comment
sg_MDL_PQL_RL	Soil gas method detection limit, practical quantitation limit, or reporting limit
sg_detect_flag_yn	Must be either "Y" for detected analytes or "N" for non_detects (soil gas)
sg_alpha_id	Unique Id for paired indoor air and soil gas results
cs_date_first	First (or only) date of crawlspace samping
cs_date_last	Last date of crawlspace sampling
cs_value_type	Crawlspace value type (actual, mean, max)

Data Fields	Data Field Descriptions
cs_result	Crawlspace result
cs_result_unit	Units of crawlspace result
cs_comment	Crawlspace result comment
cs_MDL_PQL_RL	Crawlspace method detection limit, practical quantitation limit, or reporting limit
cs_detect_flag_yn	Must be either “Y” for detected analytes or “N” for non_detects (crawlspace)
cs_alpha_id	Unique Id for paired indoor air and crawlspace results
oa_date	Date of outdoor air sample
oa_result	Outdoor air result
oa_result_unit	Units of outdoor air result
oa_detect_flag_yn	Must be either “Y” for detected analytes or “N” for non_detects (outdoor air)

Appendix C

Vapor Intrusion Database Site Information

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List of Sites

Acronym List

AEHS	Association for Environmental Health and Sciences
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CDOT-MTL	Colorado Department of Transportation Materials Testing Laboratory
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense non-aqueous phase liquid
DoD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
HVAC	heating, ventilation, and air conditioning
KDHE	Kansas Department of Health and Environment
LAFB	Lowry Air Force Base
LNAPL	light non-aqueous phase liquid
MADEP	Massachusetts Department of Environmental Protection
MI DEQ	Michigan Department of Environmental Quality
MTBE	methyl tert-butyl ether
NAPL	non-aqueous phase liquid
NJDEP	New Jersey Department of Environmental Protection
NPL	Superfund National Priorities List
NYSDEC	New York State Department of Environmental Conservation
ORD	Office of Research and Development (U.S. EPA)
PCE	tetrachloroethylene
QA/QC	quality assurance/quality control
RP	responsible party
TAGA	trace atmospheric gas analyzer
TCA	trichloroethane
TCE	trichloroethene
TNRCC	Texas Natural Resource Conservation Commission
TPH	total petroleum hydrocarbons
VC	vinyl chloride
VOC	volatile organic compound

Alameda Naval Air Station Alameda, CA

Geologic Setting

Hydrogeologic Setting: Coastal Lowlands

Groundwater Region: Alluvial Basins

Aquifer Type: Marsh and estuarine deposits

Depth to Groundwater: 1–2.4 m, average 1.5 m

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Gasoline contamination migrated below a commercial building at the Alameda Air Force site in San Francisco Bay area of California (Fischer et al., 1996). Contamination source is inferred to be residual NAPL above the water table.

Chemicals of Concern: Petroleum hydrocarbons (2-methylbutane)

Source Type: NAPL

Depth to Source: 1–2.4 m, average 1.5 m

General Surrounding Land Use: Former gas station (about 60% paved, 40% unpaved)

Comments: A vertical profile indicated a sharp decrease in hydrocarbon vapor concentrations between 0.7 m and 0.4 m depth bgs and a corresponding increase in oxygen concentrations. The iso-pentane and benzene concentrations in soil vapor at 0.7 m depth were 28,000 mg/m^3 and 200 mg/m^3, respectively.

Vapor Intrusion Investigation

Data Source: Published paper

Timeframe(s) Sampled: January 1995

Media Sampled (distance): Ambient air, indoor air, subslab, soil gas (0.7 m under building)

Indoor Survey (y/n): No

Results of Indoor Survey: NA

Number of Buildings: 1

Building Use(s): Commercial

Foundation Type(s): Slab on grade

Comments: The single-story building has a footprint of 50 m^2 and a slab-on-grade foundation. Fill soils comprised of sand underlie the building. Building was a former gas station.

Data Provenance and Quality

Data Provider: Ian Hers

Entry Process: Electronic import

Information About Data Quality. *High quality.* Data set supported by peer-reviewed publication.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. The data provider rechecked the imported data from this study against original data in paper. All data checked were correct.

References

Fischer, M.L., A.J. Bentley, K.A. Dunkin, A.T. Hodgson, W.W. Nazaroff, R.G. Sextro, and J.M. Daisy. 1996. Factors affecting indoor air concentrations of volatile organic compounds at a site of subsurface gasoline contamination. *Environmental Science & Technology 30*:2948–2957.

Allepo Mountain View, CA

Geologic Setting

Hydrogeologic Setting: Coastal Lowlands

Groundwater Region: Alluvial Basins

Aquifer Type: Alluvial basins, valleys, and fans

Depth to Groundwater: 4.5–10 ft bgs

Soil Type (Texture Code): Fine (L)

Contamination History

Discovery/Source: The dissolved groundwater plume originated from a former chemical storage and solvent recovery facility

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater

Depth to Source: 4.5–10 ft below slab

General Surrounding Land Use: Mixed industrial/residential

Vapor Intrusion Investigation

Data Source: Vapor intrusion workshop

Timeframe(s) Sampled: 2004

Media Sampled (distance): Indoor air, subslab, soil gas, and groundwater (along property boundary)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Indoor air levels are generally consistent with background outdoor air

Number of Buildings: 4

Building Use(s): Residential

Foundation Type(s): Slab on grade

Comments: Buildings are single-family homes built in 2000 with attached garages and forced-air heating and cooling.

Data Provenance and Quality

Data Provider: Loren Lund/Ian Hers

Entry Process: Hand entry

Information About Data Quality: *High quality.* Investigation overseen by EPA (as lead agency), with QA/QC protocols conforming to EPA's requirements.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source.

References

Lund, L., T. Feng, J. Su, and B. DeHghi. 2004. *Observed Versus U.S. EPA "Limited Site-Specific" Soil Gas-to-Indoor Air Attenuation Factors for a Site in a Semi-arid Climate*. Presentation at the U.S. EPA Modeling Vapor Intrusion Workshop held at the AEHS Amherst Conference on Contaminated Soils. Amherst, MA. October. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2003. *Mountain View Sites Update.* Region 9. San Francisco, CA. January. Available at http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/91f8ceee903fc0f088256f0000092934/67184eb252df98f7882570070063c355/$FILE/mew_jan03.pdf (accessed October 2007).

Alliant Techsystems (ATK) Littleton, CO

Geologic Setting

Hydrogeologic Setting: Alternating sandstone, limestone, and shale – thin soil

Groundwater Region: Nonglaciated Central

Aquifer Type: Bedded sedimentary rock

Depth to Groundwater: 3 m bgs

Soil Type (Texture Code): Fine (C)

Comments: Groundwater beneath the site is shallow. Site is underlain by claystone and sandstone.

Contamination History

Discovery/Source: Dissolved solvent plume originated from disposal activities at an electronic component manufacturing facility in the 1950s and 1960s (U.S. EPA, 2007).

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; 1,1-DCE; *cis*-DCE; VC; 1,1,1-TCA; 1,2-DCA; chloroform)

Source Type: Groundwater

Depth to Source: 3 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: Vapor intrusion workshop, EPA (Region 8) [2002 database]

Timeframe(s) Sampled: 08/2001, 01/2002

Media Sampled (distance): Indoor air; soil gas, and groundwater (30 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available

Number of Buildings: 6

Building Use(s): Residential homes

Foundation Type(s): NA

Comments: Buildings are single-family.

Data Provenance and Quality

Data Provider: L. Breyer, Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality*. Responsible party, EPA oversight indicate adequate QA/QC by EPA standards. Paired samples, information on the methodology, and good agreement between measurements and model predictions also suggest a high-quality data set.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. All data were sent to submitter for confirmation.

References

ATK (Alliant Techsystems) Inc. 2007. *Information for the community*. Alliant Techsystems Inc. Web site: http://www.atk.com/littleton/default.htm (accessed September 2007).

Breyer, L. 2004. *Measured Versus Model Predicted Attenuation at ATK Dry Creek Road Site, Littleton, Colorado*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2007. *Alliant Techsystems (ATK) RCRA Factsheet.* U.S. EPA online information. Region 8, Denver, CO. Available at http://www.epa.gov/unix0008/land_waste/ rcra/fact/alliant/alliant.html (accessed September 2007).

BP Site Paulsboro, NJ

Geologic Setting

Hydrogeologic Setting: River Alluvium without Overbank Deposits

Groundwater Region: Atlantic and Gulf Coastal Plain

Aquifer Type: River valleys and floodplains without overbank deposits

Depth to Groundwater: 19 ft bgs

Soil Type (Texture Code): Coarse (LS)

Comments: The site is underlain with relatively uniform medium sands with occasional lenses of silty or clayey sand and some gravel.

Contamination History

Discovery/Source: Groundwater contamination beneath the site originated from a line leak in the 1980s at a petroleum distribution terminal with a dissolved gasoline plume migrating off site and underneath a residential neighborhood.

Chemicals of Concern: Petroleum hydrocarbons (BTEX, TPH, methane, MTBE)

Source Type: Groundwater

Depth to Source: 3.2 m below foundation

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: Responsible party (BP)

Timeframe(s) Sampled: 1996, 1997

Media Sampled (distance): Indoor air, subslab (0.7 m deep), soil gas (average of probes on 4 sides and within a few meters of building), groundwater (average of 2 nearby wells.)

Indoor Survey (y/n): NA

Results of Indoor Survey: NA

Number of Buildings: 1

Building Use(s): Residential

Foundation Type(s): Basement

Comments: The concrete foundation of this single-family residence built in the late 1950s or early 1960s is located 1.68 m bgs, has a good integrity with little cracking, and was poured directly over natural sediments.

Data Provenance and Quality

Data Provider: Victor Kremesec (BP)/Ian Hers

Entry Process: Hand entry

Information About Data Quality: *Low quality.* Documentation is very limited and no more documentation is available. No QA/QC documentation. One of the few hydrocarbon sites in the database.

Quality Control: All data were double checked and sent to submitter for confirmation.

References

None

CDOT-MTL Denver, CO

Geologic Setting

Hydrogeologic Setting: Alternating sandstone, limestone, and shale – thin soil

Groundwater Region: Nonglaciated Central

Aquifer Type: Bedded sedimentary rocks

Depth to Groundwater: 10 ft bgs

Soil Type (Texture Code): Fine (SL)

Comments: Site is underlain by fractured Denver Formation siltstone.

Contamination History

Discovery/Source: Dissolved solvent plume resulted from releases of waste solvents from storage tanks installed in the 1970's at the CO Department of Transportation Materials Testing Laboratory.

Chemicals of Concern: Chlorinated hydrocarbons (TCE, 1,1-DCE; VC; 1,1,1-TCA)

Source Type: Groundwater

Depth to Source: 3.7 m bgs

General Surrounding Land Use: Residential

Comments: Plume intermingles with plume from nearby Redfields site

Vapor Intrusion Investigation

Data Source: State, EPA (CDOT, Region 8) [2002 database]

Timeframe(s) Sampled: 1993–1999

Media Sampled (distance): Indoor air, groundwater (interpolated)

Indoor Survey (y/n): Yes

Results of Indoor Survey: No background sources of DCE, which is the risk driver; background varied widely for other VOCs

Number of Buildings: 6

Building Use(s): Residential apartments/ townhomes

Foundation Type(s): Slab on grade

Comments: Air concentrations are average of indoor air concentrations from multiple first floor apartments.

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Publications and studies document data quality steps and validate data against vapor intrusion processes and across lines of evidence.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. All data were sent to submitter for confirmation.

References

Kurz, J. 2000. *In-Depth Review of Colorado (CDOT Facility) Data*. Presentation in August 15 Corrective Action EI Forum on Vapor Intrusion. Available at http://clu-in.org/eiforum2000/prez/28/28.pdf (accessed September 2007).

Foster, S. J., Kurtz, J.P. And Woodland, A. K. 2004. *Volatilization of Bromodichloromethane from Chlorinated Drinking Water as a Contributor to Residential Indoor Air Risk*. Available at http://www.envirogroup.com/publications/brdiclme-chloroform_paper_v2_8_23_04_publication_eleven.pdf (accessed September 2007).

Johnson, P.C., R.A. Ettinger, J. Kurtz, R. Bryan, and J.E. Kester. 2002. *Migration of Soil Gas Vapors to Indoor Air: Determining Vapor Attenuation Factors Using a Screening-Level Model and Field Data from the CDOT-MTL Denver, Colorado Site*. American Petroleum Institute Technical Bulletin Number 16:10. Available at http://www.api.org/ehs/groundwater/codot.cfm (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2002. *U.S. EPA Technical Support Project Technical Session Summary*, June 3–6, 2002, Denver, CO. Technology Innovation Office. Washington, DC. Available at http://www.epa.gov/tio/tsp/download/2002_meet/denver_2002.pdf

Davis Manufacturing Facility Troy, MI

Geologic Setting

Hydrogeologic Setting: Glacial till over bedded sedimentary rock

Groundwater Region: Glaciated Central Region

Aquifer Type: Till and till over outwash

Depth to Groundwater: 4–7 ft bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: TCE and petroleum cutting fluids released to the subsurface from the former Davis Manufacturing Facility. In 1994, investigators discovered DNAPL plume extending off-site beneath neighboring residential property.

Chemicals of Concern: Chlorinated hydrocarbons (TCE; *cis*-DCE; *trans*-DCE; VC)

Source Type: DNAPL

Depth to Source: 1.7 m bgs

General Surrounding Land Use: Residential and industrial

Vapor Intrusion Investigation

Data Source: State (MI DEQ)

Timeframe(s) Sampled: 1999–2002

Media Sampled (distance): Indoor air, soil gas, groundwater (7.5 ft from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: TCE and DCE not impacted by indoor sources; background similar to ambient air

Number of Buildings: 1

Building Use(s): Residential, industrial

Foundation Type(s): Basement

Comments: The residential building has very shallow groundwater conditions, with the water sometimes rising into the basement. A carbon filtration unit is operating in the home. The industrial building is the source of the contamination.

Data Provenance and Quality

Data Provider: Jeff Crum, MI DEQ

Entry Process: Electronic import from database

Information About Data Quality. *Medium quality*. Information was originally limited to sampling method for each media sample. Although additional information was not provided during the last review, the site investigation was conducted in a regulatory context under the auspices of MI DEQ and probably includes the appropriate QA/QC protocols and validation protocols.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were them rechecked by data submitter and original site project manager.

References

None

Denver PCE BB Denver, CO

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 12–14 ft bgs

Soil Type (Texture Code): Fine (SL)

Contamination History

Discovery/Source: Solvent plume

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; chloroform; 1,1,1-TCA); petroleum hydrocarbons (BTEX) were measured indoors but were not present in the subsurface.

Source Type: Groundwater

Depth to Source: 12–14 ft bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: EPA (Region 8)

Timeframe(s) Sampled: 2004, 2005

Media Sampled: Indoor air, subslab

Indoor Survey (y/n): Yes

Results of Indoor Survey: No significant indoor sources noted

Number of Buildings: 7

Building Use(s): Residential, commercial

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Region 8 / Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality*. Data were collected according to EPA QA/QC protocols, and are internally consistent.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. All data were sent to submitter for confirmation.

References

None

Eau Claire Eau Claire, MI

Geologic Setting

Hydrogeologic Setting: Outwash over bedded sedimentary rock

Groundwater Region: Glaciated Central Region

Aquifer Type: Sand and gravel

Depth to Groundwater: 0.6–1.2 m below foundation

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Solvent plume

Chemicals of Concern: Chlorinated hydrocarbons (TCE, *cis*-DCE, VC)

Source Type: Groundwater

Depth to Source: 0.6–1.2 m below foundation

General Surrounding Land Use: Mixed industrial/residential (data collected from three residences adjacent to Berrien Tool and Die Building).

Vapor Intrusion Investigation

Data Source: EPA (Region 8) (2002 database)

Timeframe(s) Sampled: Fall 2000

Media Sampled (distance): Indoor air, groundwater (6–10 m from building)

Indoor Survey (y/n): NA

Results of Indoor Survey: NA

Number of Buildings: 3

Building Use(s): Residential

Foundation Type(s): Basement

Comments: Indoor air samples were collected in the basements and first floors of these single-family residences. Indoor source of TCE was suspected in one house and sources of TCE and cis-DCE in another.

Data Provenance and Quality

Data Provider: Helen Dawson/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Indoor survey and sampling plan not available

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. All data were sent to submitter for confirmation.

References

None

Endicott Endicott, NY

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Glaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 20–40 ft bgs

Soil Type (Texture Code): Fine (L)

Comment: Site underlain by shale bedrock covered with unconsolidated glacial, alluvial, and fill deposits of varying thicknesses and ranging in texture from clay to gravel. Sand and gravel layers in the alluvial deposits form the surficial (water table) aquifer.

Contamination History

Discovery/Source: Groundwater contamination discovered in 1980 after a 1,1,1-TCA spill at a former manufacturing facility. Solvent plume has extended beneath adjacent and nearby residential and commercial neighborhood.

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; 1,1-DCE; *cis*-DCE; VC; 1,1,1-TCA; 1,1-DCA; chloroethane; methylene chloride; Freon 113)

Source Type: Groundwater

Depth to Source: About 25 feet below foundation

General Surrounding Land Use: Mixed residential with some commercial

Vapor Intrusion Investigation

Data Source: State (NYSDEC)

Timeframe(s) Sampled: Spring/Summer 2003; Fall 2004

Media Sampled (Distance): Ambient air, indoor air, subslab, soil gas (4–16.7 m from building), groundwater (5–13.3 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Potential indoor sources noted in many buildings.

Number of Buildings: 232

Building Use(s): Residential, institutional, commercial, multiuse

Foundation Type(s): Basement (full, partial, unspecified), slab on grade

Comment: Most buildings were constructed before World War II.

Data Provenance and Quality

Data Provider: William E. Wertz (NYSDEC)

Entry Process: Hand entry, electronic import

Information About Data Quality: *High quality*. Analytical and sampling QA/QC was adequately conducted and documented, including data validation information, results of laboratory and field duplicate samples, a formal and independent data validation and usability assessment reports. Data were assessed against data quality objectives for accuracy, precision, sensitivity, consistency, and technical usability.

Quality Control: All manual entry was double checked for accuracy. Data provider rechecked and confirmed entry of first set of data for 27 buildings. Subsequent data sets were imported from electronic sources, with manual and automated checks performed to ensure accurate data transfers from original sources.

References

New York State Department of Health. n.d. *Endicott Soil Vapor Project*. Available at http://www.health.state.ny.us/environmental/investigations/soil_gas/index.htm (accessed October 2007).

NY State Department of Environmental Quality. n.d. *Vapor and Groundwater Sampling Results, Endicott, New York*, *Environmental Investigations*. Available at http://www.dec.ny.gov/chemical/24890.html (accessed October 2007).

Fresh Water Lens Massachusetts

Geologic Setting

Aquifer Type: Surficial beach sands transitioning to deeper marine clays

Depth to Groundwater: 8–10 ft bgs

Soil Type (Texture Code): Coarse (S)

Comment: Freshwater lens present beneath site.

Contamination History

Discovery/Source: A release of TCE apparently occurred near a former underground storage tank and impacted soil and groundwater at a former industrial manufacturing site.

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Soil, groundwater

Depth to Source: 20 ft bgs

General Surrounding Land Use: NA

Vapor Intrusion Investigation

Data Source: Vapor intrusion workshop

Timeframe(s) Sampled: NA

Media Sampled (Distance): Indoor air, groundwater (NA), soil gas (NA)

Indoor Survey (y/n): Yes

Results of Indoor Survey: NA

Number of Buildings: 2

Building Use(s): Commercial

Foundation Type(s): NA

Comment: Freshwater lens appears to be impeding upward migration of contaminants.

Data Provenance and Quality

Data Provider: T.M. McAlary

Entry Process: Hand entry

Information About Data Quality: *High quality*. QA/QC conducted and documented. Consistency in multiple lines of evidence.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source.

References

McAlary, T.A., K. Berry-Spark, T.A. Krug and J.M. Uruskyj. 2004. *The Fresh Water Lens and its Effects on Groundwater to Indoor Air Attenuation Coefficients*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

Georgetown Seattle, WA

Geologic Setting

Hydrogeologic Setting: Coastal lowlands

Groundwater Region: Alluvial Basins

Aquifer Type: Alluvial basins, valleys, and fans

Depth to Groundwater: NA

Soil Type (Texture Code): (SM)

Contamination History

Discovery/Source: Dissolved groundwater plume resulting from leaking solvent tanks at former manufacturing and waste disposal facilities

Chemicals of Concern: Chlorinated hydrocarbons (PCE; 1,1,1-TCA; 1,1-DCA; chloroform; carbon tetrachloride) and xylenes

Source Type: Groundwater

Depth to Source: NA

General Surrounding Land Use: Mixed residential and industrial

Vapor Intrusion Investigation

Data Source: Vapor intrusion workshop, EPA Region 10

Timeframe(s) Sampled: August 2000

Media Sampled (Distance): Indoor air, subslab, soil gas (NA)

Indoor Survey (y/n): NA

Results of Indoor Survey: NA

Number of Buildings: 2

Building Use(s): Residential

Foundation Type(s):

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality.* Indoor air and subslab sampling conformed to EPA protocols but QA/QC documentation was not supplied.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. All data were sent to submitter for confirmation.

References

Georgetown community page: http://www.georgetownneighborhood.com/site.html.

Mayer, C., A. Sidel, C. Waldron, and K. Prestbo. 2004. *Calculation of Site Specific Groundwater to Indoor Air Volatilization Factors*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

Grants Site Grants, NM

Geologic Setting

Hydrogeologic Setting: River alluvium

Groundwater Region: Colorado Plateau and Wyoming Basin

Aquifer Type: Alluvial basins, valleys, and fans

Depth to Groundwater: 4–6 ft bgs

Soil Type (Texture Code):

Comments: Groundwater flows to the east and southeast.

Contamination History

Discovery/Source: Site was discovered by New Mexico Environment Department in 1993 during underground storage tank investigations, and groundwater investigations were conducted in 1999 and 2000. Site is underlain by multiple dissolved solvent plumes.

Chemicals of Concern: Chlorinated hydrocarbons (PCE, TCE, *cis*-DCE, VC)

Source Type: Groundwater

Depth to Source: 4–6 ft bgs

General Surrounding Land Use: Mixed residential/commercial

Comments: PCE was detected in shallow groundwater at concentrations up to 26,000 µg/L.

Vapor Intrusion Investigation

Data Source: Vapor intrusion workshop

Timeframe(s) Sampled: NA

Media Sampled (Distance): Ambient air, indoor air, background, crawlspace air, soil gas (within a few meters), groundwater (10–110 ft from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: NA

Number of Buildings: 8

Building Use(s): Residential

Foundation Type(s): 2 slab on grade, 3 crawlspace, 2 basement

Comments: Soil gas probes installed relatively close (within a few meters)

Data Provenance and Quality

Data Provider: J. Lowe/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *Low quality*. Preliminary data, widely varying soil gas concentrations.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

Comment: Soil gas is average of concentrations for 4 probes installed on 4 sides of the building,

References

Halloran, A., J. Minchak, J. Lowe, B. Thompson, S. Appaji, C. Meehan. 2004. *Attenuation Factors and Multiple Lines of Evidence for Evaluation of Potential Vapor Intrusion Pathways–Experience with the Grants Chlorinated Solvents Plume Site, Cibola County, New Mexico*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

Hamilton-Sundstrand Denver, Co

Geologic Setting

Hydrogeologic Setting: River alluvium without overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains without overbank deposits

Depth to Groundwater: 9.7 m bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Dissolved solvent plume in groundwater from past industrial solvent use.

Chemicals of Concern: Chlorinated hydrocarbons (TCE; 1,1-DCE)

Source Type: Groundwater

Depth to Source: 9.7 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: EPA Region 8 (2002 database)

Timeframe(s) Sampled: 1999–2006

Media Sampled (Distance): Indoor air, groundwater (interpolated)

Indoor Survey (y/n): NA

Results of Indoor Survey: NA

Number of Buildings: 35

Building Use(s): Residential homes

Foundation Type(s): NA

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Indoor air and subslab sampling conformed to EPA protocols but QA/QC documentation was not supplied.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

Comments: Some groundwater concentrations are estimated based on concentration contours.

References

U.S. EPA (Environmental Protection Agency). n.d. *Hamilton Sundstrand fact sheets*. U.S. EPA Region 8. Available at http://epa.gov/Region8/land_waste/rcra/fact/hamsun/hamsun.html (accessed October 2007).

Harcros/Tri State Wichita, KS

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 16–18 ft bgs

Soil Type (Texture Code): Coarse (S)

Comments: Subsurface consists of clay to 6 feet underlain by coarse sand and gravel.

Contamination History

Discovery/Source: The Tri-State Laundry and Dry-Cleaner Supply Company (Tri-State) and the Harcros Chemical Supply Company (Harcros) were identified as potential sources of groundwater contamination during an adjacent site investigation. Contamination from the adjacent site consists primarily of chlorinated solvents, mostly TCE and PCE. In May 1998, Harcros entered into an Interim Agreement with KDHE to conduct an investigation to determine if chemicals found in the groundwater were originating from their property. This investigation identified solvents, such as PCE, TCE, and 1,1,1- trichloroethane in the soil and groundwater. The City filed a lawsuit in 1998 against parties believed to be responsible for the groundwater contamination, including Tri-State and Harcros. Additional investigation conducted in association with the lawsuit confirmed these two facilities as sources of volatile organic contamination. Harcros ultimately settled the lawsuit with the City and Tri-State declared bankruptcy, leaving the City responsible for investigating and remediating the contamination associated with these facilities.

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; *trans*-DCE; 1,1-DCE; *cis*-DCE; VC)

Source Type: Groundwater

Depth to Source: 3.4–4.3 m below foundation

General Surrounding Land Use: Primarily residential, limited commercial

Vapor Intrusion Investigation

Data Source: State (KDHE)

Timeframe(s) Sampled: April 2005

Media Sampled (distance): Ambient air, indoor air, crawlspace, subslab, soil gas (NA), groundwater (NA)

Indoor Survey (y/n): Yes

Results of Indoor Survey: No potential indoor air sources for constituents of concern found within structures

Number of Buildings: 7

Building Use(s): Primarily residential, limited commercial

Foundation Type(s): Basement/crawlspace, crawlspace

Data Provenance and Quality

Data Provider: William Morris (KDHE)/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *High quality.* All soil gas and subslab samples were analyzed in the field using a gas chromatograph in a mobile lab equipped with an electron capture device, and replicate samples were sent to a fixed laboratory for consequent TO-15 analysis. Indoor air and ambient air samples were analyzed only by TO-15 methodology. All samples were collected using a site specific QAPP, and data validation was done by staff at KDHE to ensure data quality met sampling objectives.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data provider confirmed data using manual spot checks.

References

None.

Hopewell Precision Site Hopewell Junction, NY

Geologic Setting

Hydrogeologic Setting: Outwash over bedded sedimentary rock

Groundwater Region: Glaciated Central Region

Aquifer Type: Sand and gravel

Depth to Groundwater: 0.8–1.3 m below foundation

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Solvent plume from paint thinners and degreasers disposed on the ground.

Chemicals of Concern: Chlorinated hydrocarbons (TCE; 1,1,1-TCA)

Source Type: Groundwater

Depth to Source: 0.8–1.3 m below foundation

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: U.S. EPA Environmental Response Team

Timeframe(s) Sampled: January/February 2004

Media Sampled (Distance): Ambient air, indoor air, subslab, groundwater (NA)

Indoor Survey (y/n): Yes (TAGA) allowed direct detection of indoor sources

Results of Indoor Survey: TAGA used to identify and remove indoor VOC sources prior to sampling.

Number of Buildings: 19

Building Use(s): Residential single family homes

Foundation Type(s): Basement (full and partial)

Comments: Foundation depth varies from 1.3–2.8 m bgs.

Data Provenance and Quality

Data Provider: D. Mickunas/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *High quality.* TAGA provided real-time measurements that agreed well with laboratory (TO-15) measurements and allowed identification and removal of indoor sources.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data provider confirmed data using manual spot checks.

References

U.S. EPA (Environmental Protection Agency). nd. *NPL Narrative for Hopewell Precision Site*. Available at http://www.epa.gov/superfund/sites/npl/nar1720.htm (accessed October 2007).

Community group site: http://hopewell-junction-citizens-for-clean-water.org/index.html (accessed October 2007).

NY State Department of Environmental Health. n.d. *Hopewell Precision area Contamination*. Available at http://www.health.state.ny.us/environmental/investigations/hopewell/ (accessed October 2007).

Jackson Jackson, WY

Geologic Setting

Hydrogeologic Setting: Glacial mountain valleys

Groundwater Region: Western Mountain Ranges

Aquifer Type: Sand and gravel

Depth to Groundwater: NA

Soil Type (Texture Code): Coarse (LS)

Comment: Site in underlain by alluvium consisting of cobbles and silty sand.

Contamination History

Discovery/Source: Dissolved groundwater plume

Chemicals of Concern: Chlorinated hydrocarbons (PCE)

Source Type: Groundwater

Depth to Source: NA

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: EPA Region 8

Timeframe(s) Sampled: August 2002, March 2003

Media Sampled (Distance): Indoor air, crawlspace, subslab, soil gas (33 and 107 m from building), groundwater (40 m from building)

Indoor Survey (y/n): No

Results of Indoor Survey: NA

Number of Buildings: 2

Building Use(s): Residential homes and apartments

Foundation Type(s): Crawlspace, slab on grade

Comment: Two of the buildings are apartments, and the other two are single-family residences.

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Sampling was overseen by EPA and conducted following EPA protocols and QA/QC criteria.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

None

Lowry Air Force Base (LAFB) Aurora, CO

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 6.1 m bgs (average)

Soil Type (Texture Code): Coarse (LS)

Comment: Vadose zone beneath the site is sandy loam or loamy sand and fines upwards. Sand and gravel aquifer is located beneath the site.

Contamination History

Discovery/Source: Dissolved solvent plume in groundwater

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; *cis*-DCE; *trans*-DCE; 1,1-DCE; VC; 1,1,2-TCA; 1,1,1-TCA; 1,2-DCA; 1,1-DCA)

Source Type: Groundwater

Depth to Source: 0.8–9.7 m below foundation

General Surrounding Land Use:

Vapor Intrusion Investigation

Data Source: EPA Region 8 (2002 database)

Timeframe(s) Sampled: 2000–2001

Media Sampled (Distance): Ambient air, indoor air, crawlspace, subslab (NA), groundwater (23–69 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Some indoor vapor sources suspected.

Number of Buildings: 13

Building Use(s): Residential

Foundation Type(s): Basement (full and partial), basement/crawlspace, crawlspace, slab on grade

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Part of 2002 VI database, LAFB data were prepared under DoD QA/QC and have been extensively reviewed for consistency and accuracy by EPA Region 8.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Dawson, H.E. 2004. *Statistical evaluation of attenuation factors at Lowry Air Force Base, CO*. Presentation at the U.S. EPA Modeling Vapor Intrusion Workshop held at the AEHS Amherst Conference on Contaminated Soils. Amherst, MA. October. Available at http://iavi.rti.org/ WorkshopsAndConferences.cfm (accessed October 2007).

Dawson, H.E. 2002. *Evaluating Vapor Intrusion from Groundwater and Soil to Indoor Air*. Presented at EPA Brownfields Conference, Charlotte, NC. November.

Lakeside Village Shopping Center Houston, TX

Geologic Setting

Hydrogeologic Setting: Unconsolidated and semi-consolidated shallow surficial aquifer

Groundwater Region: Atlantic and Gulf Coastal Plain

Aquifer Type: Shallow unconsolidated/semi-consolidated aquifers

Depth to Groundwater: NA

Soil Type (Texture Code): Fine (L)

Comment: Subsurface consists of clay to silty clay with calcareous nodules.

Contamination History

Discovery/Source: Former dry cleaning activities at the site contaminated the underlying soil and groundwater with PCE, with presence of DNAPL and vapor clouds likely.

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; trans-DCE; cis-DCE; chlorobenzene; chloroform; 1,1,1-TCA; 1,1-DCE; 1,2-DCA; methyl chloride; 1,2-dichlorobenzene; chlorobenzene); toluene; carbon disulfide; 1,2,4-trimethylbenzene; acetone; ethanol; styrene; ethylbenzene; and xylenes

Source Type: Soil, groundwater

Depth to Source: NA

General Surrounding Land Use: Commercial

Vapor Intrusion Investigation

Data Source: State (TX Voluntary Cleanup Program)

Timeframe(s) Sampled: 1995, 1997, 2000

Media Sampled (Distance): Indoor air, subslab, groundwater (NA)

Indoor Survey (y/n): NA

Results of Indoor Survey: Former dry cleaner

Number of Buildings: 1

Building Use(s): Commercial

Foundation Type(s): Slab on grade

Comment: Building is a strip mall that hosts a dry cleaning facility currently used as a pickup/drop-off location. Off-gases from the clean clothes may contribute to indoor air contaminant concentrations.

Data Provenance and Quality

Data Provider: N. Pechacek

Entry Process: Hand entry

Information About Data Quality: *Medium quality.* Limited data validation information was included in the data package along with sampling methods. The site investigation for one site was conducted under Texas' Voluntary Cleanup Program, and the groundwater remediation plan received a Conditional Certificate of Completion by TNRCC in February 1998.

Quality Control: Manual checks were performed for 100% of hand-entered data. Data were rechecked by submitter.

References

None

Lockwood Solvent Billings, MT

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 2.4 m

Soil Type (Texture Code): Fine (L)

Comment: Subsurface consists of silty sand to silty clay.

Contamination History

Discovery/Source: The chlorinated solvent plume originated from a trailer washing areas at a former tractor trailer manufacturer. Contaminants in this chlorinated solvent plume underlying residential area may exist in either dissolved or pure product form from individual or combined sources or in the environment.

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; *cis*-DCE; *trans*-DCE; 1,1-DCE; VC; 1,1-DCA; 1,2-DCA; carbon tetrachloride)

Source Type: Soil, groundwater, NAPL

Depth to Source: 2.4 m bgs

General Surrounding Land Use: Residential and light industrial commercial

Comment: Based on current data, the contaminated groundwater plume is approximately 580 acres in area.

Vapor Intrusion Investigation

Data Source: EPA Region 8

Timeframe(s) Sampled: 2001–2002

Media Sampled (Distance): Indoor air, crawlspace, groundwater (10–450 ft from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Possible indoor vapor sources noted in two buildings.

Number of Buildings: 13

Building Use(s): Residential single family homes

Foundation Type(s): Crawlspace/basement, crawlspace, slab on grade

Comment: Residences are single-family homes, mobile homes, and modular homes.

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Data were validated according to EPA Method TO-15 and the EPA Contract Laboratory Program for National Functional Guidelines for Organic Data Review.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

U.S. EPA (Environmental Protection Agency). nd. *Lockwood Solvent Groundwater Site fact sheet*. U.S. EPA Region 8. Available at http://www.epa.gov/region8/superfund/mt/lockwood_solvents/index.html (accessed October 2007).

MADEP1 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: NA

Depth to Groundwater: 2.1 m bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Not available by site

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater

Depth to Source: 2.1 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)

Timeframe(s) Sampled: 1993–1994

Media Sampled (Distance): Indoor air, soil gas, groundwater (3 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available by site

Number of Buildings: 2

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Limited information available about individual sites.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf (accessed October 2007).

MADEP2 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: NA

Depth to Groundwater: 2.7 m bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Not available by site

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater

Depth to Source: 2.7 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)

Timeframe(s) Sampled: September 1991, January 1993

Media Sampled (Distance): Indoor air, groundwater (9.1 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available by site

Number of Buildings: 1

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Limited information available about individual sites.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf (accessed October 2007).

MADEP3 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: NA

Depth to Groundwater: 2.4 m bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Not available by site

Chemicals of Concern: Petroleum hydrocarbons (BTEX)

Source Type: Groundwater

Depth to Source: 2.4 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)

Timeframe(s) Sampled: 1995–1996

Media Sampled (Distance): Indoor air, groundwater (9 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available by site

Number of Buildings: 3

Building Use(s): Residential

Foundation Type(s): Basement, slab on grade

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Limited information available about individual sites.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf (accessed October 2007).

MADEP4 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: NA

Depth to Groundwater: 3.4 m bgs

Soil Type (Texture Code): Coarse (S)

Comment: Subsurface consists of sand and gravel

Contamination History

Discovery/Source: Not available by site

Chemicals of Concern: Petroleum hydrocarbons (BTEX)

Source Type: Groundwater

Depth to Source: 3.4 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)

Timeframe(s) Sampled: July 1994, Feb. 1995

Media Sampled (Distance): Indoor air, groundwater (4.5 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available by site

Number of Buildings: 1

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Limited information available about individual sites.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf. (accessed October 2007).

MADEP5 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA
Groundwater Region: Northeast and Superior Uplands
Aquifer Type: NA
Depth to Groundwater: 2.4 m bgs
Soil Type (Texture Code): Coarse (S)
Comment: Subsurface consists of sand.

Contamination History

Discovery/Source: Not available by site
Chemicals of Concern: Petroleum hydrocarbons (BTEX)
Source Type: Groundwater
Depth to Source: 2.4 m bgs
General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)
Timeframe(s) Sampled: 1993–1994
Media Sampled (Distance): Indoor air, groundwater (7.6 m from building)
Indoor Survey (y/n): Yes
Results of Indoor Survey: Not available by site
Number of Buildings: 1
Building Use(s): Residential
Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Helen Dawson
Entry Process: Electronic import
Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Limited information available about individual sites.
Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf (accessed October 2007).

MADEP6 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: NA

Depth to Groundwater: 0.8 m bgs

Soil Type (Texture Code): Coarse (S)

Comment: Subsurface consists of sand and gravel.

Contamination History

Discovery/Source: Not available by site

Chemicals of Concern: Petroleum hydrocarbons (BTEX)

Source Type: Groundwater

Depth to Source: 0.8 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)

Timeframe(s) Sampled: 1990, 1991, 1994

Media Sampled (Depth): Indoor air, groundwater (4.5 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available by site

Number of Buildings: 2

Building Use(s): Residential

Foundation Type(s): Basement, crawlspace

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Little information available about individual sites.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf (accessed October 2007).

MADEP7 Massachusetts

Geologic Setting

Hydrogeologic Setting: NA

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: NA

Depth to Groundwater: 2.7 m bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: Not available by site

Chemicals of Concern: Petroleum hydrocarbons (BTEX)

Source Type: Groundwater

Depth to Source: 2.7 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (MADEP) (2002 database)

Timeframe(s) Sampled: February 1995

Media Sampled (Distance): Indoor air, groundwater (6 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available by site

Number of Buildings: 1

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: [2002] Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality*. Data reviewed and analyzed by MADEP. Little information available about individual sites.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Fitzpatrick, N.A., and J.J. Fitzgerald. 1996. *An evaluation of vapor intrusion into buildings through a study of field data*. Presented at the 11th Annual Conference on Contaminated Soils, University of Massachusetts. October. Available at http://www.mass.gov/dep/cleanup/gw2proj.pdf (accessed October 2007).

Moffett MCH Mountain View, CA

Geologic Setting

Hydrogeologic Setting: Coastal lowlands

Groundwater Region: Alluvial Basins

Aquifer Type: Alluvial basins, valleys, and fans

Depth to Groundwater: 15 ft bgs

Soil Type (Texture Code): Fine (L)

Comments: Fluvial plain and tidal deposits in the area include coarse sand and gravel channels surrounded by finer grained sediments. Vadose zone is composed of silts and clays. Groundwater is under artesian conditions.

Contamination History

Discovery/Source: Chlorinated solvent plume from Moffett Naval Air Station underlies residential areas.

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater

Depth to Source: 3.66 m bgs

General Surrounding Land Use: Residential

Comments: TCE detected in shallow groundwater in 1999/2000 at ~300 μg/L.

Vapor Intrusion Investigation

Data Source: Vapor intrusion workshop

Timeframe(s) Sampled: 8/2002–5/2004

Media Sampled (Distance): Indoor air, groundwater (NA)

Indoor Survey (y/n): Yes

Results of Indoor Survey: All buildings have "ubiquitous site TCE." They are located in an urban society, with regional TCE groundwater plumes and home products containing TCE and/or construction materials.

Number of Buildings: 3

Building Use(s): Residential single family homes

Foundation Type(s): Slab on grade.

Comments: Buildings are part of community housing and were constructed in 1933 in Westcoat housing area. These vacant housing units have a 4-inch concrete slab foundation.

Data Provenance and Quality

Data Provider: D. Goldman/Ian Hers

Entry Process: Hand entry

Information About Data Quality: *High quality.* Investigation overseen by EPA (as lead agency), with QA/QC protocols conforming to EPA's requirements.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Doctor, W., R.J. Maricio, and D. Goldman. 2004. *Comparing Air Measurements and Modeling Results at a Residential Site Overlying a TCE Plume*. Presentation at the U.S. EPA Modeling Vapor Intrusion Workshop held at the AEHS Amherst Conference on Contaminated Soils. Amherst, MA. October. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2003. Mountain View Sites Update. Region 9. San Francisco, CA. January. Available at http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/91f8ceee903fc0f088256f0000092934/67184eb252df98f7882570070063c355/$FILE/mew_jan03.pdf (accessed October 2007).

Mount Holly Mt. Holly, NJ

Geologic Setting

Hydrogeologic Setting: Unconsolidated and semi-consolidated shallow surficial aquifer

Groundwater Region: Atlantic and Gulf Coastal Plain

Aquifer Type: Shallow unconsolidated/semi-consolidated aquifers

Depth to Groundwater: 6.7–7.6 ft bgs

Soil Type (Texture Code): Coarse (LS)

Comments: Site lies in Inner Plain Province within Coastal Plain Province where complex sequences of Inner Plain deposits overlie Cretaceous formations. Shallow geologic units include the Wenonah-Mount Laurel Formation (dark gray, silty sand and sand beds intercolated with dark-colored clay; up to 130 feet thick) and the underlying the Marshalltown Formation (silty, glauconitic sand; 10 to 40 feet thick). Soil deposits on a part of the site are primarily fine sand with trace clay and silt below a depth of 7 feet.

Contamination History

Discovery/Source: Petroleum hydrocarbons (gasoline) released at a former industrial site. Contamination has migrated off-site below a residential area with single-family dwellings.

Chemicals of Concern: Petroleum hydrocarbons (BTEX)

Source Type: Groundwater

Depth to Source: 0.8 m below building foundation

General Surrounding Land Use: Residential

Comments: The soil testing results suggested the presence of residual NAPL in soil; however, the NAPL was submerged below the water table during the time site monitoring was completed.

Vapor Intrusion Investigation

Data Source: State (NJDEP)

Timeframe(s) Sampled: December 2005

Media Sampled (Distance): Indoor air, groundwater (within 1 to 2 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Varies; buildings are generally old with poorly ventilated basements. Original surveys provided in NJDEP (2006).

Number of Buildings: 1

Building Use(s): Residential (single family homes)

Foundation Type(s): Basement, some with dirt floors.

Comments: The residences investigated are over 50 years old, are 3-story buildings with basements, and have foundations of variable construction ranging from concrete to partial dirt floors.

Data Provenance and Quality

Data Provider: NJDEP/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *High quality*. Well-documented study (sampling methods, boring logs, indoor air surveys, analytical results) with consistent lines of evidence.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were spot checked for accuracy by data provider.

References

NJDEP (New Jersey Department of Environmental Protection). 2006. *Investigation of Indoor Air Quality in Structures Located above VOC-Contaminated Groundwater, Year Two, Part 1: Evaluation of Soil Vapor Intrusion at Mount Holly Site, New Jersey*. Prepared by Golder Associates, Inc., Cherry Hill, NJ, for the New Jersey Department of Environmental Protection (NJDEP), Trenton, NJ. July. Available at http://www.state.nj.us/dep/dsr/air/yr2-part1-vapor-intrusion.pdf (accessed October 2007).

Mountain View Mountain View, CA

Geologic Setting

Hydrogeologic Setting: Coastal lowlands **Groundwater Region:** Alluvial Basins

Aquifer Type: Alluvian basins, valleys, and fans **Depth to Groundwater:** 10.3 m bgs

Soil Type (Texture Code): Coarse (LS)

Comments: The soils at the site consist of mostly silty/clayey sand and gravel with some sand or silt layers.

Contamination History

Discovery/Source: The subsurface contamination is believed to be associated with a leaching field where wastes were dumped.

Chemicals of Concern: Chlorinated solvent (primarily TCE)

Source Type: Groundwater **Depth to Source:** 10.3 m bgs

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: Consultant (2002 database) **Timeframe(s) Sampled:** 2000–2001

Media Sampled (Distance): Indoor air, soil gas (NA), groundwater (NA) **Indoor Survey (y/n):** Not available

Results of Indoor Survey: NA

Number of Buildings: 5 **Building Use(s):** Residential single family

Foundation Type(s): Slab on grade

Comments: Buildings are single family dwellings built in 1998 with at-grade construction and a moisture vapor barrier.

Data Provenance and Quality

Data Provider: Helen Dawson/Ian Hers **Entry Process:** Electronic import

Information About Data Quality: *Low quality*. Obtained from slide presentation; no reports available

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were spot checked for accuracy by data provider.

References

U.S. EPA (Environmental Protection Agency). 2003. *Mountain View Sites Update.* Region 9. San Francisco, CA. January. Available at http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/91f8ceee903fc0f088256f0000092934/67184eb252df98f7882570070063c355/$FILE/mew_jan03.pdf (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2007. *Intel Corp. (Mountain View Plant). Region 9 Superfund Fact Sheet*. San Francisco, CA. October. Available at http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/2e3c0ceec080b048882573290078b56a/10c6e6123e05fdb788257007005e9470 !OpenDocument (accessed October 2007).

Orion Park Mountain View, CA

Geologic Setting

Hydrogeologic Setting: Coastal lowlands
Groundwater Region: Alluvial Basins
Aquifer Type: Alluvial basins, valleys, and fans
Depth to Groundwater: 3 m below foundation
Soil Type (Texture Code): Fine (L)

Comments: Fluvial plain and tidal deposits in the area include coarse sand and gravel channels surrounded by finer grained sediments. Vadose zone is composed of silts and clays. Groundwater is under artesian conditions.

Contamination History

Discovery/Source: Chlorinated solvent plume from Moffett Naval Air Station underlies residential areas.
Chemicals of Concern: Chlorinated hydrocarbons (PCE, TCE)
Source Type: Groundwater
Depth to Source: 3 m below foundation
General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: EPA Region 9
Timeframe(s) Sampled: April/May 2005
Media Sampled: Indoor air, subslab
Indoor Survey (y/n): NA
Results of Indoor Survey: NA
Number of Buildings: 8
Building Use(s): Residential single family homes
Foundation Type(s): Slab on grade
Comments: Buildings are apartments/townhomes.

Data Provenance and Quality

Data Provider: Alana Lee/Helen Dawson
Entry Process: Electronic import
Information About Data Quality: *High quality*. Data collected according to EPA protocols

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were spot checked for accuracy by data provider.

References

U.S. EPA (Environmental Protection Agency). 2003. *Mountain View Sites Update*. Region 9. San Francisco, CA. January. Available at http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/91f8ceee903fc0f088256f0000092934/67184eb252df98f7882570070063c355/$FILE/mew_jan03.pdf (accessed October 2007).

Rapid City Rapid City, SD

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 22.5–27 ft bgs

Soil Type (Texture Code): Fine (SC)

Comments: Site is underlain by clay, silt, and sandy clay.

Contamination History

Discovery/Source: TCE groundwater plume.

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater

Depth to Source: 3.3–4.6 m below foundation

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: Responsible Party (U.S. Air Force)

Timeframe(s) Sampled: February/March 2004

Media Sampled (Distance): Indoor air, soil gas (NA), groundwater (NA)

Indoor Survey (y/n): NA

Results of Indoor Survey: NA

Number of Buildings: 3

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Data collected according to EPA protocols

QC: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by data provider.

References

None

Raymark Stratford, CT

Geologic Setting

Hydrogeologic Setting: Outwash over crystalline bedrock

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: Sand and gravel

Depth to Groundwater:

Soil Type (Texture Code): Coarse (S)

Comments: Groundwater flow heavily influenced by location and orientation of bedrock valleys

Contamination History

Discovery/Source: Chlorinated solvent plume underlying older homes originated from a former manufacturing facility. Site is now on the NPL.

Chemicals of Concern: Chlorinated hydrocarbons (TCE; *cis*-DCE; 1,1-DCE; 1,1,1-TCA; 1,1-DCA)

Source Type: Groundwater

Depth to Source:

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: U.S. EPA ORD

Timeframe(s) Sampled: See reports below

Media Sampled: Indoor air, subslab

Indoor Survey (y/n): Yes

Results of Indoor Survey: See reports below

Number of Buildings: 14

Building Use(s): Residential single family homes

Foundation Type(s): Basement

Comments: Some homes are over 100 years old.

Data Provenance and Quality

Data Provider: D. DiGuilio/Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Extensively studied site for method development and testing research conducted by EPA ORD, including extensive QA/QC and peer review of report and results.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by data provider.

References

DiGiulio, D. 2006. *Evaluation of the "Constrained Version" of the J&E Model and Comparison of Soil-Gas and Sub-Slab Air Concentrations at the Raymark Superfund Site*. Presentation at the U.S. EPA *Summary Workshop in the Context of EPA's VI Guidance Revisions* held at the AEHS 16th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 16. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

DiGiulio, D. 2004. *Sub-Slab Air Sampling Protocol and Analysis to Support Assessment of Vapor Intrusion*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2006. *Assessment of Vapor Intrusion in Homes Near the Raymark Superfund Site Using Basement and Sub-Slab Air Samples*. EPA/600/R-05/147. Office of Research and Development. Ada, OK. March. Available at http://www.epa.gov/ada/download/ reports/600R05147/600R05147.pdf (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2006. *Comparison of Geoprobe® PRT and AMS GVP Soil-Gas Sampling Systems with Dedicated Vapor Probes in Sandy Soils at the Raymark Superfund Site*. EPA/600/R-06/111. Office of Research and Development. Ada, OK. November. Available at http://www.epa.gov/ada/download/reports/600R06111/600R06111.pdf (accessed October 2007).

Redfield Denver, CO

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 0.2–40 ft bgs

Soil Type (Texture Code): (S to SI)

Comments: Subsurface consists of silty clay loess with sand lenses. Coarse-grained buried river channel acts as preferential pathway.

Contamination History

Discovery/Source: A solvent plume associated with a former rifle manufacturing operation was discovered in 1994 (Brown Group Retail, 2007).

Chemicals of Concern: Chlorinated hydrocarbons (1,1-DCE)

Source Type: Groundwater

Depth to Source: 0.2–40 ft bgs

General Surrounding Land Use: Residential and commercial

Vapor Intrusion Investigation

Data Source: Consultant for RP (2002 database)

Timeframe(s) Sampled: 1998–2003

Media Sampled (Distance): Indoor air, groundwater (interpolated)

Indoor Survey (y/n): Yes

Results of Indoor Survey: 1,1-DCE in soil gas and indoor air provides a positive indication of vapor intrusion (no indoor sources).

Number of Buildings: 330

Building Use(s): Residential single family homes

Foundation Type(s): Basement (full and partial), crawlspace, slab on grade

Comments: Extensive plume follows preferential pathway along river channel deposits to underlie many homes. Extensive work with temporal aspects of indoor air concentrations.

Data Provenance and Quality

Data Provider: D. Folkes/J. Kurtz (Helen Dawson)

Entry Process: Electronic import

Information About Data Quality: *High quality.* Extensively studied site, with many measurements that show internal consistency between lines of evidence. Good QA/QC, sampling, and documentation.

QC: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by data provider.

References

Brown Group Retail. 2007. *Redfield Site*. Brown Group Retail online information. Available at: http://www.redfieldsite.org/index.php (accessed September 2007).

Folkes, D., E. Wannamaker, and T. Kuehster. 2004. *Evaluation of Observed Groundwater to Indoor Air Attenuation Factors Redfield Site, CO*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

Kurtz, J.P., D.J. Folkes, and T.E. Kuehster. 2004. *A COC Ratio Approach for Defining Extent of Vapor Intrusion and Background*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. Available at http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

U.S. EPA (Environmental Protection Agency). 2002. *U.S. EPA Technical Support Project Technical Session Summary*, June 3–6, 2002, Denver, CO. Technology Innovation Office. Washington, DC. Available at http://www.epa.gov/tio/tsp/download/2002_meet/denver_2002.pdf

SCM Cortlandville Cortlandville, NY

Geologic Setting

Hydrogeologic Setting: Outwash over bedded sedimentary rock

Groundwater Region: Glaciated Central

Aquifer Type: Sand and gravel

Depth to Groundwater: 0.46–4.9 m below foundation

Soil Type (Texture Code): Varies across site from fine to very coarse (ML, SM, GP, GM)

Contamination History

Discovery/Source: Former Smith Corona Manufacturing facility released trichloroethene and other volatile chemicals into the soil and groundwater during its operation in Cortlandville. The resulting groundwater plume extends beneath homes to the north of the facility property line.

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater

Depth to Source: 0.46–4.9 m below foundation

General Surrounding Land Use: Residential

Vapor Intrusion Investigation

Data Source: State (NYSDEC)

Timeframe(s) Sampled: March 2006–2007

Media Sampled (Distance): Indoor air, subslab, soil gas (15–72 m from building), groundwater (interpolated)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Not available at this time

Number of Buildings: 40

Building Use(s): Residential

Foundation Type(s): Basement

Comment: Average depth to foundation is 1.5 m bgs.

Data Provenance and Quality

Data Provider: William Wertz/Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Extensively studied site, with many measurements that show internal consistency between lines of evidence. Good QA/QC, sampling, and documentation.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by data provider.

References

NYSDEC (NY State Department of Environmental Conservation). 2007. *Cortlandville Fact Sheet*. NY State Department of Environmental Conservation. Albany, NY. Available at http://www.dec.ny.gov/ docs/remediation_hudson_pdf/712006fs.pdf (accessed October 2007).

NYSDEC (NY State Department of Environmental Conservation). 2007. *Former Smith Corona Manufacturing Facility*. Site Number 712006. NY State Department of Environmental Conservation. Albany, NY. Available at http://www.dec.ny.gov/chemical/8670.html (accessed October 2007).

Stafford Stafford, NJ

Geologic Setting

Hydrogeologic Setting: Unconsolidated and semi-consolidated shallow surficial aquifer

Groundwater Region: Atlantic and Gulf Coastal Plain

Aquifer Type: Shallow unconsolidated/semi-consolidated aquifers

Depth to Groundwater: 10–11 ft bgs

Soil Type (Texture Code): Coarse (S)

Comments: Site underlain by fine to medium sand.

Contamination History

Discovery/Source: An LNAPL petroleum plume from leaking underground storage tank extends beneath the site.

Chemicals of Concern: Petroleum hydrocarbons (BTEX; MTBE; cyclohexane; 2,2,4-trimethylpentane)

Source Type: LNAPL

Depth to Source: 5–10.5 ft below foundation

General Surrounding Land Use: Mixed residential and commercial

Vapor Intrusion Investigation

Data Source: State (NJDEP)

Timeframe(s) Sampled: 2002

Media Sampled (Distance): Indoor air, subslab, soil gas (1–2 m from building), groundwater (1–2 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Identified background sources included paints, thinners, glues, and cleaning solvents (see Boyer [2002] below)

Number of Buildings: 3

Building Use(s): Mixed residential and commercial

Foundation Type(s): Basement, crawlspace/basement, slab on grade

Data Provenance and Quality

Data Provider: NJDEP/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *High quality*. Good sampling plan. Adequate QA/QC of the sampling and analysis data. Peer-reviewed publication.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were rechecked by the submitter.

References

Boyer, J.E. 2002. Background Contamination and its Impact on the Assessment of Vapor Intrusion. In *Proceedings from the U.S. EPA Seminars on Air Indoor Vapor Intrusion.* San Francisco, Dallas, and Atlanta. Dec 2002, Jan and Feb, 2003. Available at http://www.epa.gov/ttbnrmrl/625R03004/session2/Boyer_Background_files/frame.htm#slide (accessed October 2007).

Golder Associates. 2006. *Influence of Bioattenuation on Vapor Intrusion into Buildings – Model Simulations Using Semi-analytical One-Dimensional Model*. Report to New Jersey

Department of Environmental Protection, Trenton, NJ. Available at http://www.state.nj.us/dep/dsr/air/yr2-part3-biomodeling.pdf (accessed October 2007).

Sanders, P.F., and I. Hers. 2006. Vapor intrusion in homes over gasoline-contaminated ground water in Stafford, New Jersey. *Ground Water Monitoring & Remediation 26*(1): 63–72.

Twins Inn Arvada, CO

Geologic Setting

Hydrogeologic Setting: River alluvium with overbank deposits

Groundwater Region: Nonglaciated Central

Aquifer Type: River valleys and floodplains with overbank deposits

Depth to Groundwater: 11–15 ft bgs

Soil Type (Texture Code): Fine (CL, LS, SI, SL)

Comment: Site is underlain by fluvial sediments composed of sand fining up to silty clay.

Contamination History

Discovery/Source: Solvent plume migrating from chemical processing facility

Chemicals of Concern: Chlorinated hydrocarbons (PCE; TCE; *cis*-DCE; 1,1-DCE; 1,1,1-TCA; 1,1-DCA)

Source Type: Groundwater

Depth to Source: 1.4–4.5 m below foundation

General Surrounding Land Use: Mixed residential/commercial

Vapor Intrusion Investigation

Data Source: EPA Region 8

Timeframe(s) Sampled: March, July 2002

Media Sampled (Distance): Indoor air, groundwater (48–114 m)

Indoor Survey (y/n): Yes

Results of Indoor Survey: Background sources removed

Number of Buildings: 2

Building Use(s): Residential, institutional

Foundation Type(s): Basement, slab on grade

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *High quality.* Good sampling plan, data collected according to EPA QA/QC protocol.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were rechecked by the submitter.

References

U.S. EPA (Environmental Protection Agency). n.d. *U.S. EPA Region 8 fact sheet*. Available at http://www.epa.gov/Region8/sf/co/twinsinn/index.html.

Uncasville Uncasville, CT

Geologic Setting

Hydrogeologic Setting: Outwash over crystalline bedrock

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: Sand and gravel

Depth to Groundwater: 2.9 m bgs

Soil Type (Texture Code): Coarse (S)

Contamination History

Discovery/Source: NA

Chemicals of Concern: Chlorinated hydrocarbons (PCE; 1,1,1-TCA)

Source Type: Groundwater

Depth to Source: 0.9 m below foundation

General Surrounding Land Use: NA

Vapor Intrusion Investigation

Data Source: EPA Region 1 (2002 database)

Timeframe(s) Sampled: 2000–2001

Media Sampled (Distance): Indoor air, soil gas (NA), groundwater (NA)

Indoor Survey (y/n): NA

Results of Indoor Survey: NA

Number of Buildings Sampled: 4

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: Helen Dawson

Entry Process: Electronic import

Information About Data Quality: *Medium quality.* Data collected according to EPA QA/QC protocol but little information besides sample results is available.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were rechecked by the submitter.

References

None

Wall Wall Township, NJ

Geologic Setting

Hydrogeologic Setting: Unconsolidated/semi-consolidated shallow surficial aquifer

Groundwater Region: Atlantic and Gulf Coastal Plain

Aquifer Type: Shallow unconsolidated/semi-consolidated aquifers

Depth to Groundwater: 17–22 ft bgs

Soil Type (Texture Code): Coarse (S)

Comments: The study area is situated in an essentially flat region of the New Jersey Coastal Physiographic province, with the topography ranging from about 50 feet above sea level at the western edge to sea level at the Atlantic Ocean. In some areas, the natural topography has been altered by human development. For example, the roads near Sun Cleaners were constructed on slightly raised embankments and existing streams were relocated. The soils at the site consist of coastal plain sand deposits.

Contamination History

Discovery/Source: Releases from 2 former dry cleaners have generated 2 large chlorinated solvent plumes.

Chemicals of Concern: Chlorinated hydrocarbons (PCE)

Source Type: Groundwater

Depth to Source: 5.2 m below foundation

General Surrounding Land Use: Residential

Comments: The dissolved plumes emanating from the source area are over a mile long and have migrated below a mostly residential site with primarily single-family houses. While separate source areas exist to some extent, the plumes are co-mingled.

Vapor Intrusion Investigation

Data Source: State (NJDEP); EPA Region 1

Timeframe(s) Sampled: October 2001–February 2002

Media Sampled (Distance): Indoor air, groundwater (interpolated)

Indoor Survey (y/n): Yes

Results of Indoor Survey: See Appendix III in Golder Associates (2006)

Number of Buildings: 43

Building Use(s): Residential single family homes

Foundation Type(s): Basement

Comments: Foundation depth averages 3.2 m bgs.

Data Provenance and Quality

Data Provider: NJDEP/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *High Quality:* Well documented, good sampling plan, adequate QA/QC.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data provider confirmed data using spot checks.

References

Golder Associates. 2006. *Investigation of Indoor Air Quality in Structures Located above VOC-Contaminated Groundwater, Year Two, Part 2: Evaluation of Soil Vapor Intrusion at*

Wall Township Site, New Jersey. Prepared for New Jersey Department of Environmental Protection. Trenton, NJ. Available at http://www.state.nj.us/dep/dsr/air/yr2-part2-vapor-%20intrusion.pdf (accessed October 2007).

West Side Corporation Queens, NY

Geologic Setting

Hydrogeologic Setting: Outwash over crystalline bedrock

Groundwater Region: Northeast and Superior Uplands

Aquifer Type: Sand and gravel

Depth to Groundwater: 10–12 ft bgs

Soil Type (Texture Code): Very coarse

Contamination History

Discovery/Source: Dry cleaner fluid handling and distribution facility

Chemicals of Concern: Chlorinated hydrocarbons (PCE)

Source Type: Subsurface/DNAPL

Depth to Source: 15–45 ft bgs

General Surrounding Land Use: Mixed industrial/residential

Vapor Intrusion Investigation

Data Source: State (NYSDEC)

Timeframe(s) Sampled: January–April 2006

Media Sampled (Distance): Indoor air, subslab, soil gas (8–72 m from building), groundwater (6–220 m from building)

Indoor Survey (y/n): Yes

Results of Indoor Survey: No significant indoor sources identified

Number of Buildings: 53

Building Use(s): Residential

Foundation Type(s): Basement

Data Provenance and Quality

Data Provider: William Wertz/Helen Dawson/Ian Hers

Entry Process: Electronic import

Information About Data Quality: *High quality.* Third-party validated.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data provider confirmed data using spot checks.

References

NYSDEC (New York State Department of Environmental Conservation). 2006. *Structure Sampling Site Investigation Data Report. West Side Corporation*. NYSDEC Index No. 2-41-026. WA No.: D003970-24. August.

Wz CA BAY Mountain View, CA

Geologic Setting

Hydrogeologic Setting: Coastal lowlands
Groundwater Region: Alluvial Basins
Aquifer Type: Alluvial basins, valleys, and fans
Depth to Groundwater: 14 ft bgs
Soil Type (Texture Code): Fine (C)

Comments: Site is underlain by clay to 6 ft below ground surface. Below 6 ft, subsurface consists of clayey sand and gravel.

Contamination History

Discovery/Source: Manufacturing processes at the site released solvents to the subsurface.

Chemicals of Concern: Chlorinated hydrocarbons (TCE)

Source Type: Groundwater
Depth to Source: 14 ft bgs

General Surrounding Land Use: Commercial

Comments: Soil cleanup was completed in 1985, and groundwater cleanup has been under way since 1986 using extraction and treatment techniques.

Vapor Intrusion Investigation

Data Spurce: Vapor intrusion workshop
Timeframe(s) Sampled: May-December 2003
Media Sampled (Distance): Indoor air, groundwater (interpolated)
Indoor Survey (y/n): Yes

Results of Indoor Survey: No indoor sources of VOCs were identified; however, battery manufacturing occurs in one section of building.

Number of Buildings: 1
Building Use(s): Commercial
Foundation Type(s): Slab on grade

Comments: Single-story building was constructed in 1965 and has 2 HVAC systems for 2 separate use areas. Cracks in floor slab serve as entry points for vapor. The building is currently part vacant office space and part occupied. The occupied space is used to manufacture batteries

Data Provenance and Quality

Data Provider: A. Wozniak/Ian Hers
Entry Process: Hand entry

Information About Data Quality: *High quality.* Investigation overseen by EPA (as lead agency), with QA/QC protocols conforming to EPA's requirements. Study well documented in presentation. Building pressurization used to verify vapor intrusion.

Quality Control: Manual and automated checks were performed to ensure data were accurately transferred from original source. Data were checked for accuracy by the data provider.

References

Wozniak, A.A. 2004. *Case Study of TCE Attenuation from Groundwater to Indoor Air and the Effects of Ventilation on Entry Routes*. Presentation at the U.S. EPA Vapor Intrusion Workshop held at the AEHS 14th Annual West Coast Conference on Soils, Sediment and Water, San Diego, March 15–18. http://iavi.rti.org/WorkshopsAndConferences.cfm (accessed October 2007).

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Appendix D

Correcting the Henry's Law Constant for Groundwater Temperature

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Correcting the Henry's Law Constant for Groundwater Temperature

In the case of groundwater as the vapor source, the subsurface source concentration (C_{sv}) is estimated assuming that the vapor and aqueous phases are in local equilibrium according to Henry's law such that:

$$C_{sv} = H'_{TS} \times C_w$$ Equation D.1

where:

C_{sv} = vapor concentration at the source of contamination (g/cm^3-v),
H'_{TS} = Henry's law constant at the system (groundwater) temperature (dimensionless), and
C_w = concentration of volatile substance in groundwater (g/cm^3-w).

The Henry's law constants generally are reported for a temperature of 25 degrees Celsius (^oC). **Table D-1** provides these values for the chlorinated hydrocarbons in the vapor intrusion database. Average groundwater temperatures, however, are typically less than 25 ^oC. In such cases, use of the Henry's law constant at 25 ^oC may over-predict the volatility of the contaminant in water.

As described in EPA's *Soil Screening Guidance* (EPA, 1996), the dimensionless form of the Henry's law constant at the average groundwater temperature (H'_{gw}) may be estimated using the Clapeyron equation:

$$H'_{gw} = \frac{\exp\left[-\frac{\Delta H_{v,gw}}{R_c} \times \left(\frac{1}{T_{gw}} - \frac{1}{T_R}\right)\right] H_R}{R \times T_{gw}}$$ Equation D.2

where:

$\Delta H_{v,gw}$ = enthalpy of vaporization of the specific substance at the groundwater temperature (cal/mol),
T_{gw} = groundwater temperature (°K = ^oC + 273.15),
T_R = reference temperature for the Henry's law constant (298.15 ^oK),
R_C = gas constant (= 1.9872 cal/mol-^oK),
H_R = Henry's law constant for the specific substance at the reference temperature (atm-m^3/mol), and
R = gas constant (= 8.205 E-05 atm-m^3/mol-^oK).

The enthalpy of vaporization at the groundwater temperature can be approximated from the enthalpy of vaporization at the normal boiling point, as follows:

$$\Delta H_{v,gw} = \Delta H_{v,b} \left[\frac{(1 - T_{gw}/T_C)}{(1 - T_B/T_C)}\right]^{\eta}$$ Equation D.3

where:

$\Delta H_{v,gw}$ = enthalpy of vaporization at the groundwater temperature (cal/mol),
$\Delta H_{v,b}$ = enthalpy of vaporization at the normal boiling point (cal/mol),

T_C = critical temperature for specific substance (^oK),
T_B = normal boiling point for specific substance (^oK),
η = exponent (unitless), and

and all other symbols are as defined previously. Table D-1 provides the chemical-specific property values used for temperature corrections to the Henry's law constant. Table D-2 provides the value of η as a function of the ratio T_B/T_C. If site-specific data are not readily available for the groundwater temperature, then Figure 1 of the EPA fact sheet (EPA, 2001) can be used to generate an estimate.

Citations

EPA (U.S. Environmental Protection Agency). 1996. Soil Screening Guidance: Technical Background Document. EPA/540/R-95/128. Office of Solid Waste and Emergency Response. Washington, DC. Available on-line at: http://www.epa.gov/superfund/health/conmedia/soil/introtbd.htm.

EPA (U.S. Environmental Protection Agency). 2001. *Fact Sheet, Correcting the Henry's Law Constant for Soil Temperature.* Office of Solid Waste and Emergency Response, Washington, DC. Available athttp://www.epa.gov/oswer/riskassessment/airmodel/pdf/factsheet.pdf.

EPA (U.S. Environmental Protection Agency)., Regions 3, 6, and 9. 2011. Regional Screening Levels for Chemical Contaminants at Superfund Sites. November. EPA Region 3, Philadelphia, PA. Available at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm.

Lide, D.R. (Ed.). 1998. *CRC Handbook of Chemistry and Physics, 79th Ed*. Boca Raton, FL: CRC Press.

Mallard, W.G. and P.J. Linstrom (Eds.). 1998. *NIST Chemistry WebBook, NIST Standard Reference Database Number 69.* November. Gaithersburg, MD: National Institute of Standards and Technology. Available at http://webbook.nist.gov/chemistry/.

Table D-1. Chemical-Specific Parameters for Adjusting Henry's Law Coefficients for Groundwater Temperature

Chemical Abstracts Service Registry Number (CASRN)	Alphabetized List of Compounds	Henry's Law Constant @25°C		Henry's Law Constant @25°C[g]	Normal Boiling Point		Critical Temperature		Enthalpy of vaporization at the normal boiling point	
		H_R		H'_R	T_b		T_c		$\Delta H_{v,b}$	
		(atm-m^3/mol)	source	(unitless)	(°K)	source	(°K)	source	(cal/mol)	source
56-23-5	Carbon tetrachloride	2.76E-02	a	1.13E+00	3.50E+02	b	5.57E+02	h	7.13E+03	h
75-00-3	Chloroethane (ethyl chloride)	1.11E-02	a	4.54E-01	2.85E+02	b	4.60E+02	f	5.88E+03	f
67-66-3	Chloroform	3.67E-03	a	1.50E-01	3.34E+02	b	5.36E+02	h	6.99E+03	h
75-34-3	Dichloroethane,1,1-	5.62E-03	a	2.30E-01	3.30E+02	b	5.23E+02	h	6.90E+03	h
75-35-4	Dichloroethylene, 1,1-	2.61E-02	a	1.07E+00	3.05E+02	b	5.76E+02	h	6.25E+03	h
156-59-2	Dichloroethylene,cis-1,2-	4.08E-03	a	1.67E-01	3.28E+02	b	5.44E+02	h	7.19E+03	h
156-60-5	Dichloroethylene,trans-1,2-	4.08E-03	a	1.67E-01	3.28E+02	b	5.17E+02	h	6.72E+03	h
75-09-2	Methylene chloride	3.25E-03	a	1.33E-01	3.13E+02	b	5.10E+02	h	6.71E+03	h
127-18-4	Tetrachloroethylene	1.77E-02	a	7.23E-01	3.94E+02	b	6.20E+02	h	8.29E+03	h
76-13-1	Trichloro-1,2,2-trifluoroethane,1,1,2-	5.26E-01	a	2.15E+01	3.21E+02	b	4.87E+02	f	6.46E+03	f
71-55-6	Trichloroethane, 1,1,1-	1.72E-02	a	7.03E-01	3.47E+02	b	5.45E+02	h	7.14E+03	h
79-01-6	Trichloroethylene	9.85E-03	a	4.03E-01	3.60E+02	b	5.44E+02	h	7.51E+03	h
75-01-4	Vinyl chloride (chloroethene)	2.78E-02	a	1.14E+00	2.60E+02	b	4.32E+02	h	5.25E+03	h

Sources and Footnotes:

a Based on values reported in the U.S. EPA Regional Screening Tables. November 2011. Available online at: http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/xls/params_sl_table_run_NOV2011.xls

b Experimental values. USEPA 2009. Estimation Programs Interface Suite™ for Microsoft® Windows, v 4.00. United States Environmental Protection Agency, Washington, DC, USA. Available online at: http://www.epa.gov/opptintr/exposure/pubs/episuite.htm

f CRC Handbook of Chemistry and Physics, 76th Edition

h EPA (2001). FACT SHEET Correcting the Henry's Law Constant for Soil Temperature. Attachment.

g National Institute of Standards and Technology (NIST). Chemistry WebBook. Available online at http://webbook.nist.gov/chemistry/

Table D-2. Values of Exponent η as a Function of T_B/T_C

Chemical-specific ratio T_B/T_C	H
< 0.57	0.30
0.57 - 0.71	$0.74 (T_B/T_C) - 0.116$
> 0.71	0.41