Evaluation of USEPA's Empirical Attenuation Factor Database

Stephen Song[1]; Francis C. Ramacciotti[1]; Barry A. Schnorr[1]; Michael Bock[2]; Christopher M. Stubbs[3]

[1]ENVIRON International Corp., 214 Carnegie Center, Princeton, NJ 08540
[2]ENVIRON International Corp., 136 Commercial Street, Portland, ME 04101
[3]ENVIRON International Corp., 6001 Shellmound Street, Emeryville, CA 94608

ABSTRACT

In its 2002 draft vapor intrusion guidance, USEPA recommended default attenuation factors for the generic screening step of a tiered vapor intrusion assessment process, in which generic screening is followed by semi-site-specific screening and then site-specific assessment. These default generic attenuation factors were based on a database of empirical attenuation factors calculated from measurements of indoor air, soil gas, and groundwater from different sites. In 2008, USEPA provided an updated database which was accompanied by a preliminary evaluation and statistical analysis. The updated database has been perceived by some regulators as being sufficiently robust to support not only the selection of attenuation factors for generic screening, but also to obviate the need for semi-site-specific screening and site-specific modeling. Our evaluation of the updated database found that: (1) most of the new empirical attenuation factors are from a small number of sites that represent a relatively narrow set of soil and building characteristics; (2) more robust techniques could be applied to further segregate empirical attenuation factors that likely have been influenced by background sources; and (3) the upper-percentile sub-slab soil gas attenuation factors are higher than can be supported by a mass balance analysis considering the ranges of observed soil gas entry rates and building ventilation rates. These findings indicate that the updated database is not sufficiently robust to obviate semi-site-specific screening or site-specific modeling. In addition, the selection of a sub-slab soil gas attenuation factor for generic screening should carefully consider the influence of background sources on indoor air measurements, and include a check against realistic ranges of soil gas entry rates and building ventilation rates.

INTRODUCTION

USEPA's 2002 draft vapor intrusion guidance[1] recommended default attenuation factors for the generic screening step of a tiered vapor intrusion assessment process, in which the generic screening step is followed by semi-site-specific screening and then site-specific assessment. As discussed in the 2002 draft guidance, the default attenuation factors of 0.1 for subslab soil gas and 0.001 for groundwater were based on an USEPA database of empirical attenuation factors calculated using measurements of indoor air, soil gas, and groundwater from different sites. The default attenuation factor of 0.01 for deep soil gas (more than 5 feet below a building foundation) was based on USEPA's belief that this value should be between those for groundwater and subslab soil gas. The default attenuation factors were to be used in generic screening but not in the semi-site-specific or the site-specific steps of the tiered process.

In 2008, USEPA made available an updated database of empirical attenuation factors and a draft report[2] describing a preliminary evaluation of the updated database. The draft report noted that the updated database contains a much larger number of attenuation factors than the 2002 database. It also reported on a statistical analysis of the empirical attenuation factors in the 2008 database and suggested that the analysis supports the 2002 default subslab and groundwater attenuation factors. The 2008 statistical analysis found the subslab attenuation factor of 0.1 to be the 95th percentile (it was the 85th percentile in 2002), and the groundwater attenuation factor of 0.001 to be the 95th percentile (as it was in 2002). For soil gas, the 2008 analysis found the attenuation factor of 0.01 to be the 50th percentile, and 0.3 to be the 95th percentile.

As USEPA works on issuing final vapor intrusion guidance in response to the December 2009 Office of Inspector General report[3], the 2008 database and the draft 2008 report are likely to be cited as bases for a number of updates to the 2002 draft guidance. It is likely that USEPA is intending to include default attenuation factors in the final guidance that are based on the 2008 database and statistical analysis. Also, USEPA staff has made statements at conferences suggesting that it is considering the use of default attenuation factors not only for generic screening but also to replace the use of other methods of estimating attenuation factors in semi-site-specific screening and site-specific assessment which is allowed in the 2002 draft guidance.

In light of the potential importance of the 2008 database and statistical analysis in setting final vapor intrusion guidance, we conducted an evaluation of the 2008 database to gain insight on: (1) whether the 2008 database is robust enough to support the identification of default attenuation factors that could obviate the need for estimating attenuation factors to account for site-specific considerations in semi-site-specific screening or in a site-specific assessment; and (2) whether the default attenuation factors recommended in 2002 and in the 2008 draft report are reasonable for generic screening.

REPRESENTATIVENESS OF THE DATABASE

If USEPA intends to rely on the 2008 database and statistical analysis to derive default attenuation factors that would limit the use of other methods for estimating attenuation factors in semi-site-specific screening and site-specific assessment, then an important question is whether the empirical attenuation factors in the database are representative of the types of site settings for which semi-site-specific screening or site-specific assessment is often used. It is important to determine the extent to which the database can support the identification of default attenuation factors that would be appropriate for the range of conditions likely to be encountered, such as residential versus nonresidential buildings, high- verses low-permeability soils, mild versus severe climate regions, biodegradable versus recalcitrant contaminants, or shallow versus deep sources. USEPA's draft 2008 report provided some summary statistics but it did not provide a breakdown that facilitates an evaluation of the types of situations that are represented by the attenuation factors in the database.

Table 1 shows a breakdown of the attenuation factors by two factors that are important for judging the relevance of the 2008 database to the vapor intrusion assessment for a particular site or a particular building. The 2,989 attenuation factors in the database are categorized by building type and soil type for each type of attenuation factor (subslab, soil gas, groundwater, and crawl space). The table also shows a breakdown of the 1,038 attenuation factors that formed the basis of the conclusions of the 2008 statistical analysis (identified as "USEPA's Data Set 2"; the selection of these data is described below).

Table 1: Empirical attenuation factors in USEPA's 2008 database and Data Set 2 (DS2)

	Subslab				**Soil Gas**				**Groundwater**				**Crawl Space**			
	Residential		Other		Residential		Other		Residential		Other		Residential		Other	
Soil Type	DS2	All	DS2	All	DS2	All	DS2	All	DS2	All	DS2	All	DS2	All	DS2	All
Very Coarse	17	82	0	0	7	68	0	0	17	83	0	0	0	0	0	0
Coarse	144	967	71	330	35	62	11	17	261	500	10	20	25	74	0	0
Fine	19	71	2	6	32	81	0	0	300	444	8	11	20	36	0	0
Unknown	58	128	0	0	1	9	0	0	0	0	0	0	0	0	0	0
Sum	**238**	**1248**	**73**	**336**	**75**	**220**	**11**	**17**	**578**	**1027**	**18**	**31**	**45**	**100**	**0**	**0**

As shown in Table 1, a vast majority of attenuation factors are for residential buildings, both in the database (2,605 or 87%) and in Data Set 2 (936 or 90%). The rest of the attenuation factors are for commercial buildings and other buildings designated as being institutional or for multiple-use. Among the attenuation factors for residential buildings, nearly 70% are for residential buildings with basements. As noted in the 2008 draft report, many of the attenuation factors for residential buildings are from a limited number of sites. The sites that contributed most of these attenuation factors are Endicott, Lowry Air Force Base, Redfield, Grants, and West Side Corporation. These five sites contributed 75% of these attenuation factors.

Table 1 also shows that most of the attenuation factors are for coarse-grain soil or very coarse-grain soil, both in the database (2,203 or 74%) and in Data Set 2 (598 or 58%). Fine-grain soil attenuation factors comprise 22% of the database and 37% of Data Set 2. However, most of these are groundwater attenuation factors. Approximately 43% of the groundwater attenuation factors in the database and 52% of the groundwater attenuation factors in Data Set 2 are for fine-grain soil. Few of the subslab, soil gas, and crawl space attenuation factors are for fine-grain soil. The database lacked soil type information for 5% of the attenuation factors, which are almost entirely those for subslab.

Another aspect of the database is that almost all of the attenuation factors in the database are for chlorinated volatile organic compounds (VOCs), primarily trichloroethene (TCE) and tetrachloroethene (PCE), and not petroleum hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX). In fact, less than 3% of the attenuation factors in the database are for BTEX, and Data Set 2 included only 5 attenuation factors for BTEX.

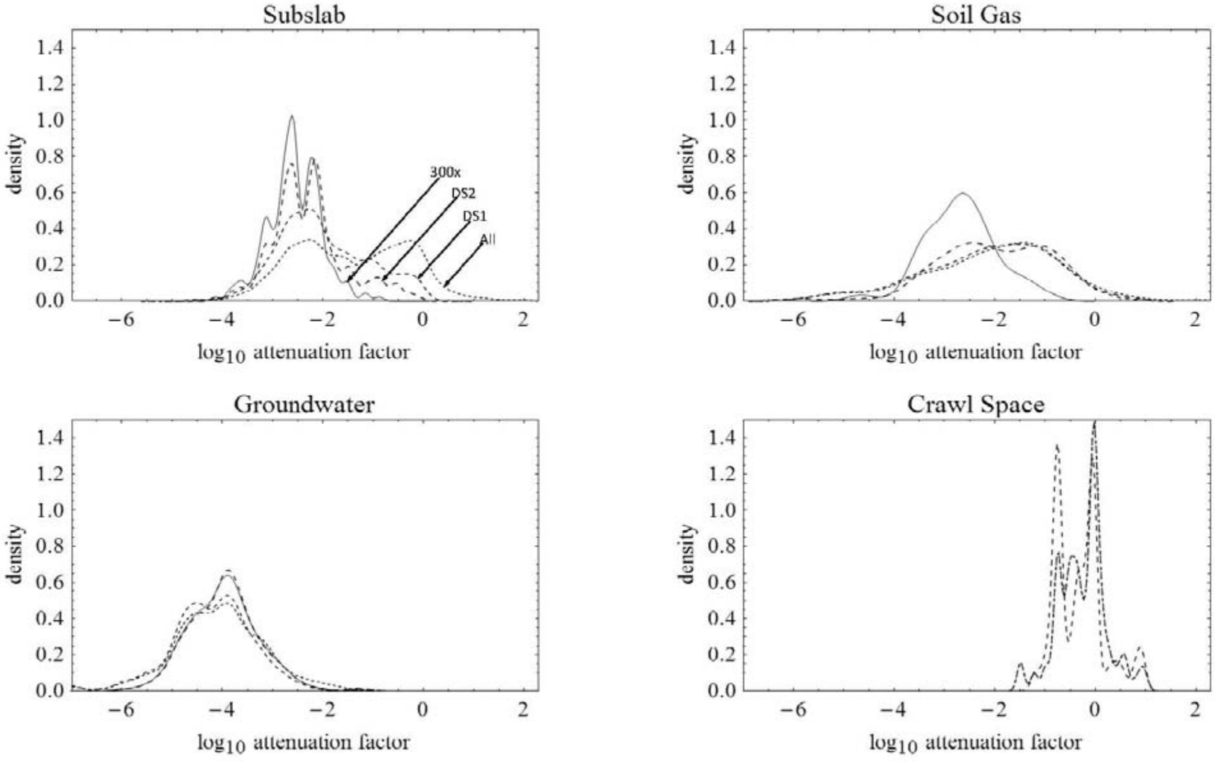
Other aspects, such as the depth of a contaminant source (especially in combination with other factors such as soil type), can affect the potential for vapor intrusion at a particular site. Hence, it would useful to know if the 2008 database has adequate representation by attenuation factor for these other aspects. However, breakdown of the database by such additional aspects is not readily feasible, if at all, because information on such aspects is not included in the database.

ELIMINATING OBVIOUS BIAS

Much of the discussion in the 2008 draft report was concerned with excluding attenuation factors from the statistical analysis. USEPA began by excluding 760 (25%) of the attenuation factors because: (1) field notes indicated the presence of a background source; (2) the indoor air concentration is higher than the subsurface concentration; or (3) the attenuation factor for a chemical is inconsistent with the attenuation factors for other chemicals in the same sample. The result was called Data Set 1. USEPA then excluded an additional 1,191 (40%) attenuation factors because they were calculated using indoor air concentrations lower than the 95th percentile indoor air background level or analytical reporting limits. The result after excluding these attenuation factors was called Data Set 2, which USEPA used in the statistical analysis.

Overall, USEPA excluded 65% of the attenuation factors before performing its statistical analysis. The percent excluded for the four attenuation factor types are: 80% for subslab, 64% for soil gas, 59% for crawl space, and 44% for groundwater. Figure 1 shows the distributions of the attenuation factors in the database (All), in Data Set 1 (DS1), and in Data Set 2 (DS2). The distribution labeled as “300x” in the subslab, soil gas, and groundwater graphs is discussed in the next section.

Figure 1: Distribution of log-transformed attenuation factors as bias is reduced



As shown in Figure 1, the exclusion of unusable attenuation factors had the most effect on the distribution of the subslab attenuation factors. The initial distribution is bimodal with one peak near 1 and the other peak near 0.01. A substantial part of the distribution (9%) exceeds 1, and ranges to 125. The parts of the distribution near 1 and higher than 1 were excluded from Data Set 1. This leveled off the first peak, but left a substantial part of the area under the peak in Data Set 1. This area is further reduced by excluding many more attenuation factors in Data Set 2. However, the distribution of Data Set 2 still includes a portion of the area from the first peak, even though 80% of the subslab attenuation factors were excluded.

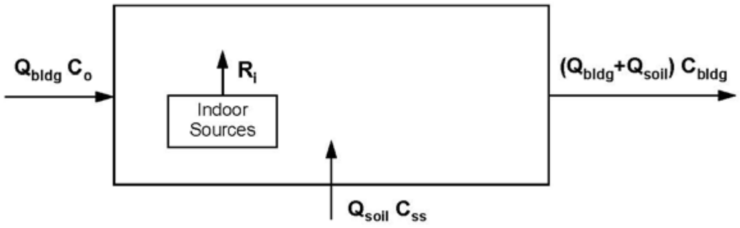
In contrast, the exclusion of unusable soil gas and groundwater attenuation factors to form Data Set 1 and Data Set 2 had a much less noticeable effect on the distributions. The distributions for Data Set 2 are not noticeably different from the distributions for Data Set 1 or the initial distributions, even though a substantial percent of attenuation factors were excluded (44% for groundwater and 64% for soil gas). These distributions also do not have a substantial portion of their area near 1 or exceeding 1.

As discussed in the 2008 draft report, the main reason for excluding the vast majority of the attenuation factors was because of concerns about the effect of indoor sources on the calculation of empirical attenuation factors. While it is appropriate to exclude empirical attenuation factors higher than 1 and those calculated based on indoor air concentrations likely to be within background levels, it does not necessarily mean that all the remaining attenuation factors were unaffected by indoor sources. For example, Data Set 2 still has subslab attenuation factors as high as 0.9, which means the indoor air concentration was almost the same as the subslab concentration (60 and 68 μg/m^3, respectively, in this case). It is very likely that this and other attenuation factors in Data Set 2 are biased high by indoor sources.

FURTHER REDUCING BIAS

To investigate the degree to which empirical subslab attenuation factors can be biased by indoor sources, we considered the combined effects of indoor sources and vapor intrusion for a single-zone, well-mixed indoor space that is ventilated with outdoor air at rate Q_{bldg}, as shown in Figure 2. A chemical in subslab soil gas enters the indoor space at a soil gas entry rate Q_{soil} and concentration C_{ss}, and soil gas entry via diffusion is assumed to be negligible which is almost always the case.

Figure 2: Mass balance for subslab soil gas entry into building



Q_{bldg}	Outdoor air flow rate through building
Q_{soil}	Subslab soil gas entry rate
C_o	Concentration in outdoor air
C_{bldg}	Concentration in building indoor air
C_{ss}	Concentration in subslab soil gas
R_i	Rate of generation from indoor sources

If the chemical is not in outdoor air and is not emitted by indoor sources, and recognizing that Q_{soil} should be much lower than Q_{bldg}, the steady-state mass balance equation for the chemical is:

Equation 1

$$Q_{soil}C_{ss} - Q_{bldg}C_{bldg} = 0$$

where: C_{bldg} is the chemical concentration in the indoor air. Solving this equation for the ratio C_{bldg}/C_{ss} gives:

Equation 2

$$\alpha_{ss} \equiv \frac{C_{bldg}}{C_{ss}} = \frac{Q_{soil}}{Q_{bldg}}$$

where: the ratio C_{bldg}/C_{ss} is the subslab soil gas attenuation factor α_{ss}. In this case, in which the subsurface is the only source of the chemical, the calculation of an empirical attenuation factor from measurements of C_{bldg} and C_{ss} should give a reasonable estimate of α_{ss}.

If the chemical is not in the subslab soil gas but is emitted by indoor sources at a rate R_i, the mass balance equation becomes:

Equation 3

$$R_i - Q_{bldg}C_{bldg} = 0$$

Solving this equation for R_i shows that the indoor sources' emission rate R_i can be written as:

Equation 4

$$R_i = Q_{bldg}C_{bldg} = Q_{bldg}C_i$$

where the chemical concentration in indoor air due solely to indoor sources is relabeled as C_i.

If the chemical is in subslab soil gas at concentration C_{ss} and emitted by indoor sources at a rate R_i, the mass balance equation becomes:

Equation 5

$$Q_{soil}C_{ss} + Q_{bldg}C_i - Q_{bldg}C_{bldg} = 0$$

Solving this equation for the ratio C_{bldg}/C_{ss} gives:

Equation 6

$$\tilde{\alpha}_{ss} \equiv \frac{C_{bldg}}{C_{ss}} = \frac{Q_{soil}}{Q_{bldg}} + \frac{C_i}{C_{ss}}$$

The ratio C_{bldg}/C_{ss} in this case is an empirical attenuation factor $\tilde{\alpha}_{ss}$. It is the attenuation factor α_{ss} plus a term for the indoor sources. This additional term biases the attenuation factor, and the bias will be noticeable when the magnitude of the term is comparable to or larger than $\alpha_{ss} = Q_{soil}/Q_{bldg}$. The degree of bias depends on the size of the term relative to Q_{soil}/Q_{bldg}.

The size of the ratio Q_{soil}/Q_{bldg} can be estimated by considering plausible values for each parameter in the ratio. For residential buildings, USEPA's guidance on vapor intrusion modeling[4] has recommended default values for both Q_{soil} and Q_{bldg}. For Q_{soil}, USEPA recommended a rate of 5 L/min. For Q_{bldg}, USEPA recommended a residential building with a basement that is 10 m by 10 m, has a mixing height of 3.66 m, and an air exchange rate of 0.25/hr. These assumptions correspond to a ventilation rate of 1,525 L/min. The ratio of these numbers is 0.003.

This estimate of Q_{soil}/Q_{bldg} can be considered to be conservatively high because USEPA chose Q_{soil} to be conservatively high and Q_{bldg} to be conservatively low. The value of Q_{soil} for residential buildings has been found to range from less than 1 L/min to as high as 10 L/min in several studies[5, 6, 7, 8]. The higher end of this range is generally associated with large pressure differences that are unlikely to be sustainable over the long term. As such, Q_{soil} could be at least five times lower or two times higher than 5 L/min. The value of Q_{bldg} could be 67% lower for a residential slab-on-grade building with a mixing height of 2.44 m. However, the air exchange rate of 0.25/hr is low for an average value over the long-term and is low for minimizing indoor source effects on indoor air quality. For example, ASHRAE Standard 62.2 recommends ventilation rates for acceptable indoor air quality in residential buildings that correspond to air exchange rates of approximately 0.5/hr or higher (after accounting for outdoor air infiltration)[9]. Finally, choosing Q_{soil} and Q_{bldg} independently and inversely of each other is conservative in itself, because in situations with high Q_{soil} due to large building under-pressurization, stack effects will tend to increase Q_{bldg}.

As another point of reference, the ratio of 0.003 can be compared with analysis based on radon entry into single-family homes. Radon is a useful tracer because there is no indoor source and the concentration in soil is relatively constant. Based on a mean indoor radon concentration and an estimate of radon concentrations in soil pores, a representative ratio of 0.0016 was estimated[10], which is comparable to the ratio of 0.003.

Taking 0.003 as the ratio of Q_{soil}/Q_{bldg}, equation (6) shows that C_i/C_{ss} will bias α_{ss} by a factor of 2 or more when it is 0.003 or higher. This means the subslab concentration C_{ss} must be approximately 300 times higher than the indoor air concentration due to indoor source C_i , to calculate empirical attenuation factors $\tilde{\alpha}_{ss}$ that are minimally biased by the effects of indoor sources.

USEPA's Data Set 2 included empirical attenuation factors that were calculated using subslab concentrations that were as little as 2 times higher than the indoor background level (e.g., 1.7 μg/m^3 of TCE in subslab, 1 μg/m^3 of TCE in indoor air, and background TCE of 0.8 μg/m^3). In Data Set 2, 72 (23%) of the 311 subslab attenuation factors were calculated from subslab concentrations less than 300 times higher than the background level. As such, nearly a quarter of the subslab attenuation factors in Data Set 2 are likely to be biased by effects of indoor sources, notwithstanding USEPA's effort to minimize such effects in constructing this data set.

Removing these 72 attenuation factors and 22 other attenuation factors for chemicals that lack a background level gave a data set with 217 subslab attenuation factors that are less likely to be greatly biased by indoor sources (i.e., by no more than a factor of 2). The distribution of this data set (300x) is shown in Figure 1 for comparison with the distributions for the database, Data Set 1, and Data Set 2. Figure 1 shows that the distribution of the new data set excludes almost all of the area under the peak with a mode of approximately 1 in the initial data set. As a point of reference, the 95th percentile of the new data set is 0.018 as compared with 0.15 for Data Set 2.

Applying this approach to Data Set 2 for soil gas attenuation factors produced similar results. For soil gas attenuation factors in Data Set 2, 40 (47%) of 86 attenuation factors were calculated from soil gas concentrations less than 300 times higher than background levels. Removing these 40 and 2 more for chemicals that lack a background level left 44 attenuation factors. The distribution of the new data set is shown in Figure 1. Similar to the new subslab data set, the new soil gas data set excludes much of the area under the peak in Data Set 2 with a mode at approximately 0.1. As a point of reference, the 95th percentile of the new data set is 0.029 as compared with 0.33 for Data Set 2.

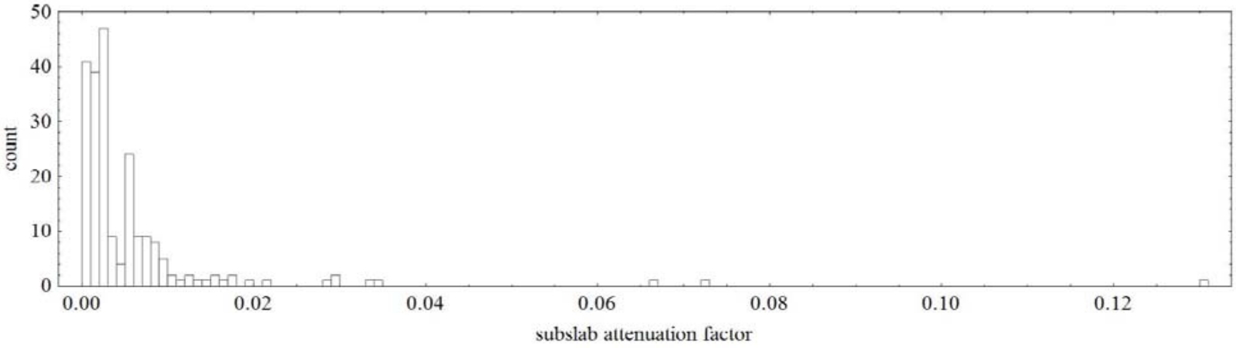
Applying the approach to Data Set 2 for groundwater attenuation factors produced little change. The reason is that only 3 (0.5%) of the 596 groundwater attenuation factors in Data Set 2 were calculated from groundwater vapor concentrations less than 300 times higher than background levels and 16 (3%) were for chemicals that lack a background level. Removing these 19 attenuation factors had no noticeable effect on the distribution. As a point of reference, the 95th percentile is 0.0015.

The approach could not be applied to Data Set 2 for crawl space attenuation factors because the 45 crawl space attenuation factors in Data Set 2 were all calculated from crawl space concentrations less than 300 times higher than background levels or for chemicals that lack a background level. None of the crawl space concentrations were higher then approximately 50 times background levels.

After applying the approach to the subslab and soil gas attenuation factors in Data Set 2, a nontrivial proportion of the remaining attenuation factors are still higher than 0.003. A review of these attenuation factors found that a large number of these subslab attenuation factors are noted in the database as having "confounding factors" which indicate that the attenuation factors are potentially affected by indoor sources (e.g., the note "Potential VOC sources noted. Observed attenuation factors for TCA and DCA may be biased high due to a confounding indoor source." is associated with an attenuation factor for 1,1,1-trichloroethane of 0.11). Additionally, some of the attenuation factors in this data set differ from other attenuation factors for the same sample by more than a factor of 10, which should have been excluded from Data Set 1 according to the discussion in the 2008 draft report. In total, 97 (45%) of the 217 subslab attenuation factors, 2 (5%) of the 44 for soil gas, and 49 (8%) of the 577 for groundwater have one or more of these characteristics, which indicates that indoor air concentrations in these cases may have been higher than the 95th percentile indoor air background concentration USEPA used in the 2008 draft report.

Some of the subslab and soil gas attenuation factors that remain after trimming Data Set 2 are also statistical outliers (more than 1.5 times the interquartile range above the third quartile or below the first quartile). For the log-transformed subslab attenuation factors, there are 3 high outliers and 4 low outliers. The untransformed subslab attenuation factors have 19 high and no low outliers. The distribution of the 217 subslab attenuation factors is shown without log-transformation in Figure 3, which gives a clearer picture of the distribution's skewness than Figure 1. The cutoff for identification of high outliers is at approximately 0.013. USEPA's default value of 0.1 is well beyond this cutoff and far out on the right tail of the distribution (99.5th percentile).

Figure 3: Distribution after further bias reduction (without log-transform)



The 44 remaining soil gas attenuation factors have no high outliers and one low outlier, with log-transformation. Without log-transformation, there are 5 high and no low outliers. The cutoff for high outliers is at approximately 0.024. USEPA's default value of 0.01 is at approximately the 88th percentile.

SUMMARY

Our evaluation found that approximately 90% of the attenuation factors in the 2008 database and statistical analysis are for residential buildings. Nonresidential buildings were represented in the statistical analysis by only 73 attenuation factors for subslab, 11 for soil gas, 18 for groundwater, and none for crawl space. The evaluation also found that most of the subslab and soil gas attenuation factors are for coarse-grain or very coarse-grain soil, and about half the groundwater attenuation factors are for fine-grain soil. Fine-grain soil is represented in the statistical analysis by 21 attenuation factors for sublab, 32 for soil gas, and 308 for groundwater. These findings indicate that the 2008 database and statistical analysis are focused on residential scenarios with coarse-grain soil, and provide little information on vapor intrusion scenarios involving nonresidential buildings or fine-grain soil (except they provide a reasonable representation of scenarios with residential buildings on fine-grain soil over chlorinated VOC groundwater sources). The database also consists almost entirely of data for chlorinated VOCs and includes very little data for petroleum hydrocarbons such as BTEX.

In conducting its statistical analysis, USEPA excluded a majority of the attenuation factors in the 2008 database because of various considerations related to the reliability of the empirical attenuation factor estimates. Most of the attenuation factors were excluded because of concerns with the effect of indoor sources. Although USEPA excluded many attenuation factors for this reason, we found the remaining ones to include many that are still likely to have been affected by indoor sources. To identify such attenuation factors, we performed a mass balance analysis of an indoor space that is subject to the effects of both indoor sources and vapor intrusion. This analysis showed that to calculate empirical attenuation factors for residential buildings with minimal bias due to indoor sources the subsurface concentrations should be at least 300 times higher than potential background indoor air levels.

A large proportion of the subslab and soil gas empirical attenuation factors USEPA used in the statistical analysis (Data Set 2) were calculated with subsurface concentrations less than 300 times higher than potential background indoor air levels. Excluding these from Data Set 2 greatly reduced the right tail of these attenuation factor distributions (e.g., the 95th percentiles dropped by approximately 10-fold). In contrast, virtually no groundwater attenuation factor in Data Set 2 warranted exclusion on this basis. Conversely, all of the crawl space attenuation factors in Data Set 2 warranted exclusion.

In summary, the findings of this evaluation show that large numbers of empirical attenuation factors in the 2008 database are likely to be biased high by the effects of indoor sources, and the prevalence of such attenuation factors is greater than recognized by the exclusion criteria used in constructing the data sets used in the 2008 statistical analysis. Our analysis shows that an important additional criterion is the consideration of the magnitude of subsurface concentrations relative to potential background indoor air levels. Application of this criterion to the 2008 database removes many of the upper percentile subslab and soil gas attenuation factors in Data Set 2, which were calculated with subsurface concentrations that are insufficiently high to give reliable estimates. Removing these attenuation factors still leaves a number of attenuation factors that are higher than predicted by our mass balance analysis. A review of these attenuation factors shows that at least some of them may have been affected by indoor sources to a greater degree than could be accounted for by the indoor air background levels that USEPA used in the 2008 statistical analysis, which we also used in our analysis.

REFERENCES

1. *OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)*; U.S. Environmental Protection Agency: Washington, DC, 2002.
2. *U.S. EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors*; U.S. Environmental Protection Agency: Washington, DC, 2008.
3. *Lack of Final Guidance on Vapor Intrusion Impedes Efforts to Address Indoor Air Risks*; Office of Inspector General; U.S. Environmental Protection Agency: Washington, DC, 2009.
4. *User's Guide for Evaluating Subsurface Vapor Intrusion Into Buildings*; U.S. Environmental Protection Agency: Washington, DC, 2004.
5. Nazaroff, W.W.; Lewis, S.R.; Doyle, S.M.;Moed, B.A.; Nero, A.V. *Environ. Sci. Technol.* **1987**, *21*, 459-466.
6. Garbesi, K.; Sextro, R.G. *Environ. Sci. Technol.* **1989**, *23*, 1481-1487.
7. Garbesi, K.; Sextro, R.G.;Fisk, W.J.;Modera, M.P; Revzan, K.L., *Environ. Sci. Technol.* **1993**, *27*, 466-473.
8. Fischer, M.L.; Bentley, A.J.; Dunkin, K.A.; Hodgson, A.T.; Nazaroff, W.W.; Sextro, R.C.; Daisey, J.M. *Environ. Sci. Technol.* **1996**, *30*, 2948-2957.

9. *ASHRAE Standard 62.2-2007: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, 2007.
10. Little, J.C; Daisey, J.M.; Nazaroff, W.W. *Environ. Sci. Technol.* **1992**, *26*, 2058-2066.

KEY WORDS

vapor intrusion, empirical attenuation factors, background indoor air, USEPA database