Evaluation of EPA's Empirical Attenuation Factor Database

by Stephen Song, Francis Ramacciotti, Barry Schnorr, Michael Bock, and Christopher Stubbs

Stephen Song, Ph.D., is a principal, **Francis C. Ramacciotti** is a manager, and **Barry A. Schnorr** is a senior associate at Environ's Princeton, NJ office; **Michael J. Bock, Ph.D.,** is a manager at Environ's Portland, ME office; and **Christopher M. Stubbs, Ph.D., P.E.,** is a senior manager at Environ's Emeryville, CA office.

The U.S. Environmental Protection Agency's (EPA) 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 (i.e., "non-generic 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As discussed in the 2002 draft guidance, the default attenuation factors of 0.1 for subslab soil gas and 0.001 for groundwater were based on an EPA database of empirical attenuation factors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 was based on EPA'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 non-generic assessment steps of the tiered process.

In 2008, EPA made available an updated database of empirical attenuation factors and a draft report[2] describing a preliminary evaluation of the database. The draft report noted that the updated database contains a much larger number of attenuation factors than in 2002. 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.

As EPA works on issuing final vapor intrusion guidance,[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the 2008 database and the draft 2008 report are likely to be cited as bases for a number of updates to the 2002 draft guidance.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 EPA is intending to include default attenuation factors in the final guidance that are based on the

Copyright 2011 Air & Waste Management Association

2008 database and statistical analysis. Also, EPA appears to be 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 the non-generic assessment allowed in the 2002 draft guidance.

In light of the potential importance of the draft 2008 report in setting final vapor intrusion guidance, we conducted an evaluation of this 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 the non-generic assessment; and (2) whether the default attenuation factors recommended in the 2008 draft report are reasonable for generic screening.

Representativeness of the Database

If EPA 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 non-generic assessments, then an important question is whether the empirical attenuation factors in the database are representative of the range of site conditions for which non-generic assessment is often used (e.g., residential versus nonresidential, high- vs. low-permeability soils, shallow versus deep sources).

Table 1 shows a breakdown of the four types of attenuation factors by soil type and building type, which are important for judging the relevance of the 2008 database to the vapor intrusion assessment for a particular site/building. The table also shows a breakdown of the attenuation factors in the database and the attenuation factors that formed the basis of the conclusions of the 2008 statistical analysis (identified as "Data Set 2" [DS2]).

As shown in Table 1, a vast majority of attenuation factors are for residential buildings, both in the database (87%) and in DS2 (90%). As indicated in the 2008 draft report, five sites contributed 75% of the attenuation factors for residential buildings.

Table 1 also shows that most of the attenuation factors are for coarse-grain soil or very coarse-grain soil. Fine-grain soil attenuation factors comprise 22% of the database and 37% of DS2, which are mostly groundwater attenuation factors. Approximately 43% of the groundwater attenuation factors in the database and 52% of the groundwater attenuation factors in DS2 are for fine-grain soil.

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 and tetrachloroethene, and not petroleum hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX). In fact, DS2 included only five 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

Table 1. Empirical attenuation factors in EPA'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**

Copyright 2011 Air & Waste Management Association

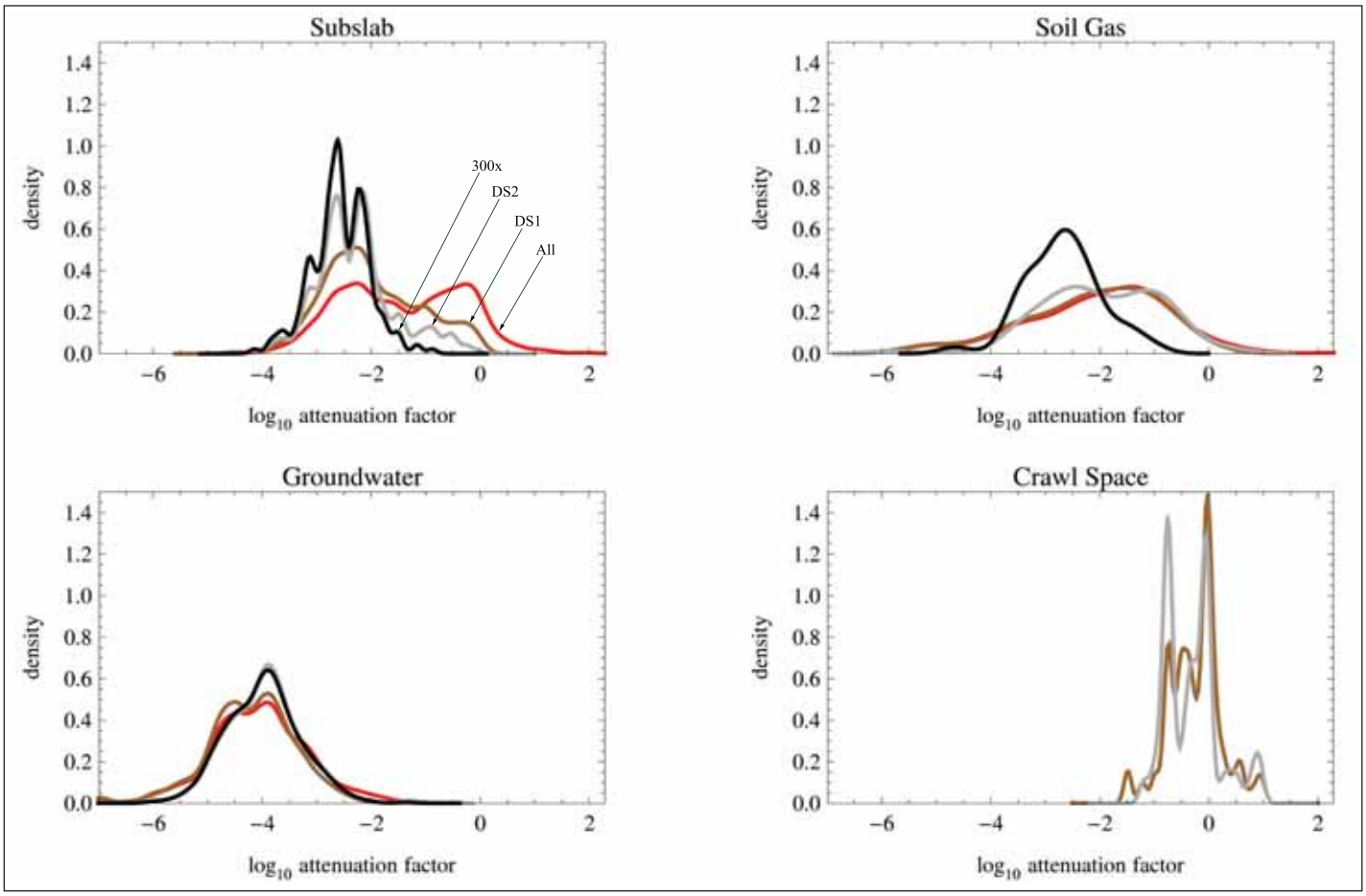

Figure 1. Distribution of log-transformed attenuation factors as bias is reduced.

aspects. However, breakdown of the database by such additional aspects was not possible because information on such aspects is not included.

Eliminating Obvious Bias

Much of the discussion in the 2008 draft report was concerned with excluding attenuation factors from the statistical analysis. EPA began by excluding 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 Data Set 1 (DS1). EPA then excluded an additional 40% of the attenuation factors because they were calculated using indoor air concentrations lower than the 95th percentile indoor air background level or below analytical reporting limits. The result after excluding these attenuation factors was DS2.

Overall, EPA excluded 65% of the attenuation factors before performing its 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 DS1, and in DS2. The distribution labeled as "300x" in the subslab, soil gas, and groundwater graphs is discussed below.

As shown in Figure 1, the exclusion of unusable attenuation factors had the most effect on the distribution of the subslab attenuation factors where the initial distribution is bimodal with one peak near 1 and the other near 0.01. The area under the first peak was reduced, but not completely eliminated, through exclusion of 80% of the subslab attenuation factors. In contrast, the exclusion of unusable soil gas and groundwater attenuation factors had a much less noticeable effect on the distributions, even though a substantial percent of attenuation factors were excluded.

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 empirical attenuation factors. While it is appropriate to exclude empirical

Copyright 2011 Air & Waste Management Association

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, DS2 still has subslab attenuation factors as high as 0.9, which means the indoor air concentration was almost equal to the subslab concentration (60 and 68 $\mu g/m^3$, respectively, in this case). It is very likely that this and other attenuation factors in DS2 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.

A mass balance analysis for this indoor space gives the following equation for the empirical attenuation factor $\tilde{\alpha}_{ss}$:

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

where C_i is the indoor air concentration due solely to indoor sources. It can be shown by mass balance analysis that the ratio Q_{soil}/Q_{bldg} represents the true attenuation factor (without effects of any indoor source). Thus, the empirical attenuation factor is the true 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 size of the ratio Q_{soil}/Q_{bldg} can be estimated by considering plausible values for each parameter in the ratio. For residential buildings, EPA's guidance on vapor intrusion modeling[4] has recommended default values for both Q_{soil} and Q_{bldg}. For Q_{soil}, EPA recommended a rate of 5 L/min. For Q_{bldg}, EPA recommended a residential building with a basement that is 100 m^2, has a mixing height of 3.66 m, and air exchange of 0.25/hr,

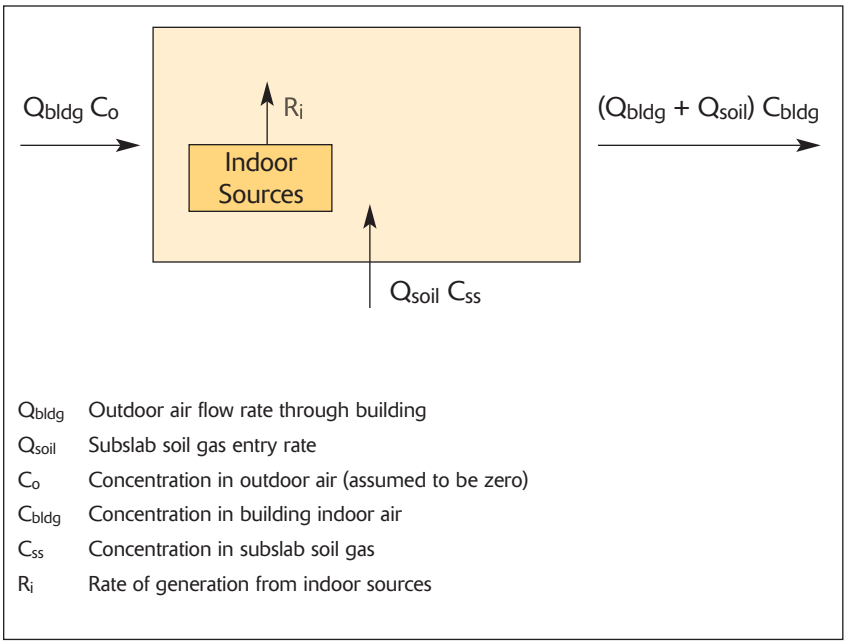

Figure 2. Mass balance for subslab soil gas entry into building.

which corresponds 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 EPA chose Q_{soil} to be conservatively high[5-8] and Q_{bldg} to be conservatively low.[9] Additionally, 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}.

Taking 0.003 as the ratio of Q_{soil}/Q_{bldg}, the equation for $\tilde{\alpha}_{ss}$ 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 that are minimally biased by the effects of indoor sources.

EPA's DS2 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 $\mu g/m^3$ of trichloroethylene (TCE) in subslab, 1 $\mu g/m^3$ of TCE in indoor air, and background TCE of 0.8 $\mu g/m^3$). In DS2, 72 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 DS2 are likely to be biased by effects of indoor sources.

Copyright 2011 Air & Waste Management Association

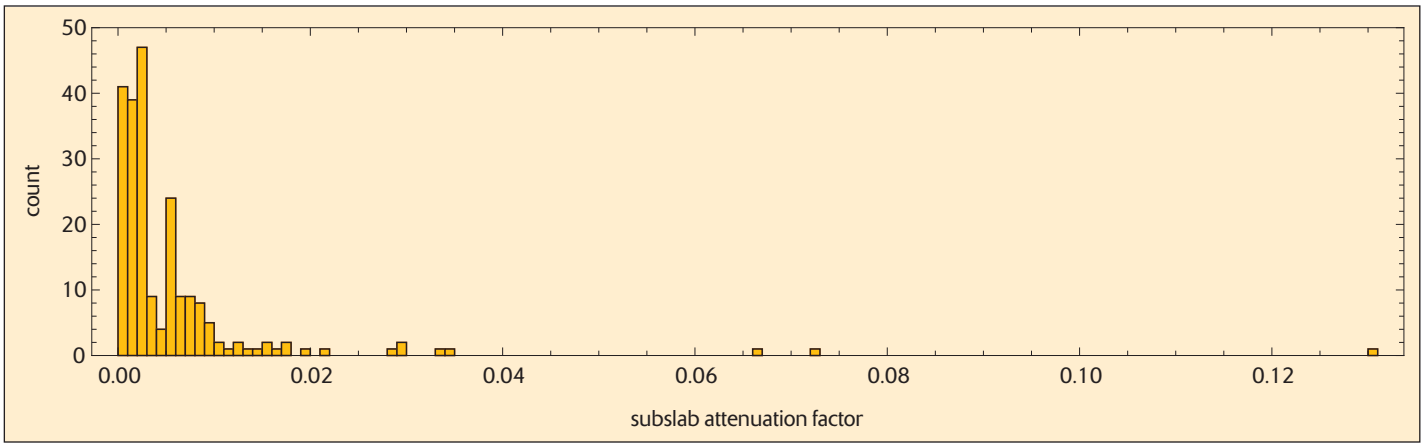

Figure 3. *Distribution after further bias reduction (without log-transform).*

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 database, DS1, and DS2. 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 DS2.

Applying this approach to DS2 for soil gas attenuation factors produced similar results. For soil gas attenuation factors in DS2, 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, whose distribution is shown in Figure 1. The 95th percentile of the new data set is 0.029 as compared with 0.33 for DS2.

Applying the approach to DS2 for groundwater attenuation factors produced little change. The reason is that only 3 of the 596 groundwater attenuation factors in DS2 were calculated from groundwater vapor concentrations less than 300 times higher than background levels and 16 were for chemicals that lack a background level.

After applying the approach to the subslab and soil gas attenuation factors in DS2, 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 DS1, according to the discussion in the 2008 draft report. In total, 45% of the 217 subslab attenuation factors, 5% of the 44 for soil gas, and 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 EPA used in the 2008 draft report.

Some of the subslab and soil gas attenuation factors that remain after trimming DS2 are also statistical outliers. The subslab attenuation factors (without log-transform) have 19 high and 0 low outliers. The distribution of the 217 untransformed subslab attenuation factors is shown in Figure 3, which gives a clearer picture of the distribution's skewness than Figure 1. The cutoff for identification of high outliers is approximately 0.013. EPA's default value of 0.1 is well beyond this cutoff and is at the 99.5th 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, and 18 for groundwater.

Copyright 2011 Air & Waste Management Association

The evaluation also found that most of the subslab and soil gas attenuation factors are for coarse-grain or very coarse-grain soil, and approximately 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 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 (e.g., BTEX).

In conducting its statistical analysis, EPA 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 EPA excluded many attenuation factors for this reason, we found the remainder 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 for 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 EPA used in the statistical analysis (DS2) were calculated with subsurface concentrations less than 300 times higher than potential background indoor air levels. Excluding these from DS2 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 factors in DS2 warranted exclusion on this basis.

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 DS2, 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 EPA used in the 2008 statistical analysis, which we also used in our analysis. **em**

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. *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. Experiments on Pollutant Transport from Soil into Residential Basements by Pressure-Driven Air Flow; *Environ. Sci. Technol.* **1987**, *21*, 459-466.
6. Garbesi, K.; Sextro, R.G. Modeling and Field Evidence of Pressure-Driven Entry of Soil Gas into a House Through Permeable Below-Grade Walls; *Environ. Sci. Technol.* **1989**, *23*, 1481-1487.
7. Garbesi, K.; Sextro, R.G.; Fisk, W.J.; Modera, M.P; Revzan, K.L. Soil-Gas Entry into an Experimental Basement: Model Measurement Comparisons and Seasonal Effects; *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. Factors Affecting Indoor Air Concentrations of Volatile Organic Compounds at a Site of Subsurface Gasoline Contamination; *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.

Copyright 2011 Air & Waste Management Association