Evaluation of Spatial and Temporal Variability in VOC Concentrations at Vapor Intrusion Investigation Sites.

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Thomas E. McHugh and Tim N. Nickels, GSI Environmental, Inc.

Samuel Brock, Air Force Center for Environmental Excellence

GSI Environmental, Inc, .2211 Norfolk, Suite 1000, Houston, TX 77098-4044
Tel: 713-522-6300, Fax: 713-522-8010
temchugh@gsi-net.com

ABSTRACT

As vapor intrusion has become an increasing concern at corrective action sites, the USEPA and a number of state regulatory agencies have recently issued guidance documents covering the collection of subsurface gas, and above-ground air samples during vapor intrusion investigations. Most of these guidance documents do not provide specific recommendations concerning the number of each type of sample required to evaluate the presence or absence of a vapor intrusion impact and, in fact, the number of samples needed to evaluate vapor intrusion depends on both the spatial and temporal variability in VOC concentrations in the environmental media sampled.

Through the collection of a large number of samples focused around individual buildings at two study sites, we have been able to evaluate the spatial and temporal variability in VOC concentration in groundwater, well headspace, soil gas, sub-slab, ambient air, and indoor air samples. At both test sites, we observed higher spatial variability in subsurface gas samples than in above-ground air samples. This indicates that a larger number of spatially-separated samples are required to accurately characterize average VOC concentrations in these media. For example, six subslab samples would be required to estimate the mean VOC concentration with an accuracy of +/- 67% while only one indoor air sample or two ambient air samples would be required to achieve the same level of accuracy.

For all media, short-term temporal variability (i.e., a time scale of days) was low, with 65% of paired samples showing a relative percent difference (RPD) of less than 30%, the standard quality assurance objective for duplicate samples. Longer-term temporal variability (i.e., a time scale of months) was significantly higher than short-term variability and was similar in magnitude to the observed spatial variability for subsurface gas samples. These findings indicate that collecting multiple samples from the same sampling point over a period of days provides little additional information concerning average VOC concentrations. However, multiple sample events spaced over a period of months do provide an improved understanding of average VOC concentrations over time at the sampling points.

Key Words: vapor intrusion, variability, attenuation factor, PCE, TCE

INTRODUCTION

Accounting for spatial and temporal variability in important for planning an efficient and effective investigation program at corrective action sites. For example, USEPA guidance documents provide tools to calculate the number of soil samples required to characterize a site based on known or estimated spatial variability[1]. In addition, quarterly groundwater monitoring was originally intended to characterize temporal variability across seasons[2]. However, USEPA and state vapor intrusion guidance documents provide disparate recommendations on how to address spatial and temporal variability in VOC distribution. For indoor air sampling, USEPA guidance recommends the collection of at one sample in "both the probable place of highest concentration (e.g., basement) and in the main living area" for "two or more sampling events" and also recommends that "multiple simultaneous samples be taken for every sampling event and from the same inlet"[3]. New Jersey guidance also specifies one basement and one first floor sample for two sampling events[4]. California guidance does not address the number of indoor air samples, but also requires at least two sampling events[5]. For subslab soil gas, USEPA guidance recommends the collection of samples from "several locations". California guidance requires at least two sample locations and recommends one sample location for every 1000 ft^2 of foundation area while New Jersey indicates that one subslab sample is sufficient for a typical residence (approximately 1500 ft^2). New Jersey generally requires two subslab sampling events while USEPA and California do not provide specific requirements to characterize temporal variability. Other guidance documents such as the ITRC guidance mention the issue of spatial and temporal variability but do not provide specific recommendations on how to address it[6]. Thus, available guidance recognize the importance of spatial and temporal variability but there is little regulatory consensus on how to address variability during a vapor intrusion investigation.

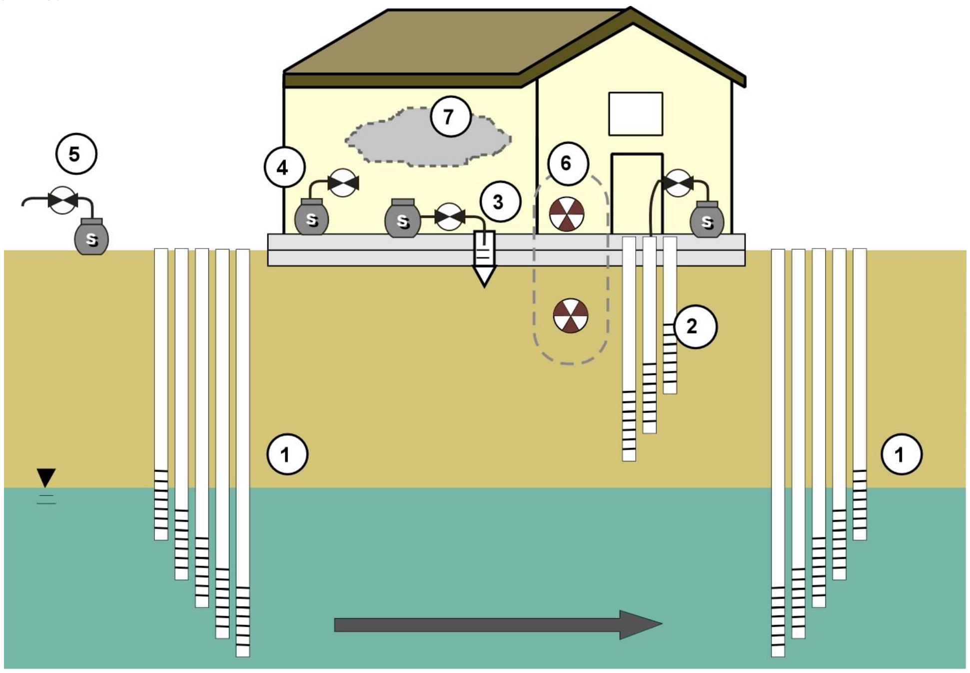
As part of a detailed investigation of vapor intrusion processes at two DOD facilities located in Oklahoma and Utah, we have collected and analyzed a large number of samples focused around individual buildings. This data set has allowed us to evaluate the spatial and temporal variability in VOC concentration in groundwater, well headspace, soil gas, sub-slab, ambient air, and indoor air samples. In this paper, we describe the spatial and temporal variability in VOC concentrations observed at these two sites and discuss how these results can be used to help plan an efficient vapor intrusion investigation.

SITE INVESTIGATION PROGRAM

We have completed detailed vapor intrusion site investigations at a total of three buildings located at two study sites: two single-family residences near Hill AFB and a small office building at Altus AFB. The investigation program consisted of sample point installation, two complete sampling events at the Hill AFB site, and four complete sampling events at the Altus AFB site. Each building was located above groundwater containing dissolved TCE (Hill AFB) or PCE and TCE (Altus AFB) and was located >1,000 ft from a known solvent release location. As a result, groundwater was believed to be the only significant source of chlorinated VOCs in subsurface gas samples.

At each of the three study buildings, three sample clusters were installed. Each sample cluster consisted of an ambient air sample point, and indoor air sample point, a sub-slab sample point, three vertically-spaced soil gas sample points, and four vertically-spaced groundwater sample points. At each building, one set of vertically-spaced soil gas sample points was installed below the building and the other two were installed adjacent to the building. The sampling network, conceptually illustrated in Figure 1 was designed to yield a high density of data around each of the investigation buildings.

Figure 1 Conceptual data collection plan for detailed evaluation of the vapor intrusion: 1) Multi-level discrete depth groundwater samples upgradient, midgradient and downgradient of the building; 2) multi-level soil gas sampling conducted below and adjacent to the building (three locations); 3) three sub-slab soil gas samples; 4) three indoor air samples, 5) three ambient air samples, 6) analysis of radon; 7) tracer gas released within the building allows for accurate measurement of building air exchange rate.



For each sampling event, samples were collected from each sample point and analyzed for VOCs. In addition, SF_6 was used as a tracer gas to measure indoor air exchange and radon was used as a naturally-occurring tracer to track gas movement through the building foundation. A typical sampling program is summarized in Table 1. The resulting data set allowed for the quantitative evaluation of spatial and temporal variability in VOC concentrations in various environmental media at the study sites.

Table 1 Summary of Sample Collection and Analysis Program for a Typical Sampling Event

Matrix	Number of Samples	Sample Volume	Sample Type	Container	Analytical Method
GW	Up to 16	3 x 40 mL	Grab	VOA Vial w/HCL	8260B (VOCs)
Well Headspace	6	400 mL*	Grab	Summa*	TO-15* (VOCs)/SF6
Soil Gas	9	400 mL*	Grab	Summa*	TO-15* (VOCs)/SF6
Sub-slab Gas	3	400 mL*	Grab	Summa*	TO-15* (VOCs)/SF6
Indoor Air	3	6 L*	24 hr	Summa*	TO-15 SIM* (VOCs)
Indoor Air Tracer	6	250 mL	Grab	Tedlar Bag	SF6
Ambient	3	6 L*	24 hr	Summa*	TO-15 SIM* (VOCs)
Ambient Radon	1	100 mL	Grab	Tedlar Bag	Mathieu, 1998 (Radon)
Indoor Air Radon	3	100 mL	Grab	Tedlar Bag	Mathieu, 1998 (Radon)
Sub-slab Radon	3	100 mL	Grab	Tedlar Bag	Mathieu, 1998 (Radon)

Note: 1) * = For the initial sampling event at each demonstration building, VOC analyses were conducted by Method 8260B using an on-site mobile laboratory with a detection limit of 5 ug/m^3, with a subset of duplicate samples analyzed off-site for validation purposes. For the on-site analyses, 50 mL samples were collected using 60 mL gas tight syringes. 2) Number of samples does not include additional samples collected for QA/QC.

RESULTS

Variability between sample measurements has been characterized through the calculation of the coefficient of variation for data sets consisting of three or more matched measurements (i.e., spatial variability at all study sites and longer-term temporal variability at the Altus AFB site). For data sets with only two matched measurements (i.e., analytical and sampling variability, shorter-term variability at the Altus AFB site and longer-term variability at the Hill AFB site), variability has been characterized through calculation of the relative percent difference (RPD) between the two measurements.

Analytical and Sampling Variability

Analytical variability was characterized through the evaluation of laboratory duplicates and surrogate recoveries. For all analyses, analytical variability was very low. For 18 duplicate analyses for PCE and TCE by TO-15, the RPD ranged from 0% to 8%, with an average of 2.5%. Surrogate recoveries for TO-15 analyses ranged from 84% to 110% with most recoveries between 98% and 102% (results not shown).

For field duplicate samples, the data quality objective (RPD<30%) was achieved for 78% of field duplicate VOC measurements. Out of 51 field duplicate paired analyses where a VOC was detected in at least one sample, 40 (78%) showed an RPD of <30%, 7 (14%) showed an RPD of 30 to 100% and 4 (8%) showed an RPD of >100%. Well headspace and soil gas samples showed the highest levels of field duplicate variability (See Table 2).

Field duplicate variability is a combined measure of analytical variability, sample collection variability, and very small scale spatial and temporal variability (i.e., variability on the scale of inches and minutes). For Summa canister samples, field duplicate samples could also be impacted by carry-over contamination due to reuse of the canisters, however, individually certified clean canisters were used for this study reducing the potential for carry-over contamination to impact duplicate variability. The field duplicate variability was higher than the laboratory variability indicating that sample collection variability and small-scale field variability were important relative to analytical variability.

Table 2: Evaluation of Variability in Field Duplicate Samples

	Number of Duplicate Analyses			
Environmental Medium	**Total**	**RPD < 30%**	**RPD 30-100%**	**RPD > 100%**
Groundwater	17	17	0	0
Well Headspace	3	2	1	0
Soil Gas	11	6	2	3
Sub-slab	7	6	1	0
Indoor	10	8	2	0
Ambient	3	1	1	1

Note: A duplicate analysis is one COC measured in field duplicate at one sample location during a field event and detected during at least one of the two samples. Analysis includes PCE, TCE, and cis-1,2-DCE in groundwater and well headspace samples and PCE and TCE in soil gas, sub-slab, indoor, and ambient samples.

Spatial Variability

Spatial variability in VOC concentration was characterized through the collection of samples from three sampling clusters located around each study building, upgradient, midgradient, and downgradient relative to groundwater flow direction. The collection three spatially separated samples from each environmental medium allowed us to characterize the spatial variability within each medium during each sample event. Spatial variability has been characterized by calculation of the coefficient of variation (CV) for each case in which the target VOC was detected in at least two of the three samples collected. The CV (i.e., standard deviation divided by sample mean) is a normalized measure of variability that is independent of the measurement scale and therefore can be compared between sample sets. In order to characterize lateral (rather than vertical) variability in subsurface samples, spatial variability for soil gas and groundwater sampling points was characterized using the results from the deepest point sampled at each cluster. Spatial variability for well headspace samples was characterized using the shallowest sample from each cluster. The results of the analysis of spatial variability are summarized in Table 3.

Table 3: Spatial Variability in VOC Concentration

Sample Medium	Number of Data Sets (1)	Average Coeff. of Variation (CV)
ABOVE-GROUND AIR		
Ambient Air	6	0.55
Indoor Air	8	0.26
SUBSURFACE GAS		
Subslab	12	0.96
Soil Gas	7	0.96
Well Headspace	13	0.92
GROUNDWATER		
Groundwater	10	0.90
GW (Altus)	6	1.35
GW (Hill)	4	0.21

Note: 1) Each data set consists of three chemical concentration measurements (TCE or PCE) with at least two detects from one environmental medium collected during a single sampling event. Number of data sets is different for each medium due to differences in frequency of VOC detection.

As shown in Table 3, the spatial variability in subsurface samples was higher than the spatial variability in above ground samples, a result expected based on greater mixing of air above ground. Although variability was low in above-ground samples compared to below-ground samples, above-ground samples are more likely to be impacted by other sources of VOCs, confounding the evaluation of vapor intrusion[7]. Spatial variability was similar for all three types of subsurface gas samples (i.e., subslab, soil gas, and well headspace) indicating that all three types of samples provide a similar quality of information about the VOC concentration in soil gas. Specifically, the similarity in variability between deep soil gas points and well headspace samples suggests that the collection of headspace samples from existing shallow groundwater wells may be a useful alternative to installation of new deep soil gas points for the characterization of VOC concentrations in deep soil gas. For groundwater, a large difference in spatial variability was observed between the Hill AFB demonstrations sites and the Altus AFB demonstration site. This difference is likely explained by the observation of a confining layer above the water-bearing unit at Altus AFB. Most of the groundwater monitoring wells at the Altus site were installed within this confining layer to characterize VOC concentrations between the water-bearing unit and the deep soil gas. VOC concentrations within this confining layer were more variable than at the top of the unconfined water-bearing unit at Hill AFB. For the other environmental media evaluated, spatial variability was similar at the Altus and Hill demonstration sites.

Temporal Variability

Short-Term Variability: Temporal variability in VOC concentration on the time scale of days was evaluated at the Altus AFB study site by collecting two samples from each sample point two days apart. An evaluation of short-term temporal variability in indoor and ambient air samples was not possible due to the prevalence of non-detect results in these media during the evaluation of short-term temporal variability. For subsurface samples, low temporal variability was observed in COC concentrations between the two sample events. Out of 31 paired analyses where a VOC was detected in at least one sample, 20 (65%) showed a RPD of <30% (i.e., <1.35x difference), indicating that these analyses would satisfy the typical data quality objective for duplicate samples. 9 paired analyses (29%) showed an RPD of 30 to 100% (i.e., 1.35 to 3x difference) while only 2 (6%) showed an RPD of >100%. The statistical analysis of short-term temporal variability is summarized in Table 4.

Table 4: Evaluation of Short-Term (days) Temporal Variability

Environmental Medium	**Number of Paired Analyses: Event 1 and Event 2**			
	Total	**RPD < 30%**	**RPD 30-100%**	**RPD > 100%**
Groundwater	7	6	1	0
Well Headspace	6	1	3	2
Soil Gas	11	7	4	0
Sub-slab	6	6	0	0
Indoor	1	0	1	0
Ambient	0	N/A	N/A	N/A

Note: A paired analysis is one COC measured at one sample location during both sample events and detected during at least one event. Analysis includes PCE, TCE, and cis-1,2-DCE in groundwater and well headspace samples and PCE and TCE in soil gas, sub-slab, indoor, and ambient samples.

The short-term temporal variability was only somewhat higher than that observed for field duplicate samples (see Table 2) indicating that the variability on the time scale of days was largely influenced by sample collection and/or very small-scale field variability. These results provide an indication that short-term temporal variability in COC concentration is not a major source of uncertainty in the evaluation of the vapor intrusion pathway.

Longer-Term Temporal Variability, Hill AFB: At the Hill AFB demonstration site, temporal variability on the time scale of months was characterized by comparing paired samples from August 2005 and March 2006 from each sample location. Longer-term temporal variability at Hill AFB was greater than short-term temporal variability at Altus AFB. Out of 39 paired analyses where a VOC was detected in at least one sample, 14 (36%) showed a relative percent difference (RPD) of <30% (i.e., <1.35x difference), indicating that these analyses would satisfy the typical data quality objective for duplicate samples. 17 paired analyses (44%) showed an RPD of 30 to 100% (i.e., 1.35 to 3x difference) while 8 (20%) showed an RPD of >100% (i.e., >3x difference). The statistical analysis of longer-term temporal variability at Hill AFB is summarized in Table 5.

Table 5: Evaluation of Longer-Term (months) Temporal Variability, Hill AFB

Environmental Medium	Number of Paired Analyses: Event 1 and Event 2			
	Total	RPD < 30%	RPD 30-100%	RPD > 100%
Groundwater	16	8	7	1
Well Headspace	6	3	3	0
Soil Gas	5	0	3	2
Sub-slab	3	0	0	3
Indoor	6	2	3	1
Ambient	3	1	1	1

Note: A paired analysis is one COC measured at one sample location during both sample events and detected during at least one event. Non-detect samples with elevated detection limits not included in analysis

Although the temporal variability in subsurface gas samples (i.e., sub-slab, soil gas, and well headspace) appears to be somewhat higher than in above-ground air samples (i.e., indoor and ambient) or groundwater samples, at least 50 % of paired samples from all media had an RPD of greater than 30%, indicating significant variability between samples.

Longer-Term Temporal Variability, Altus AFB: At the Altus AFB demonstration site, the completion of three sampling events allowed for a more comprehensive statistical analysis of longer-term temporal variability. For Altus AFB, longer-term temporal variability has been evaluated using the coefficient of variation (CV) for each case in which the target VOC was detected in at least two of the three temporally-separated samples collected from each sample point. The results of the analysis are summarized in Table 6. Temporal variability at indoor and ambient sample points could not be evaluated due to non-detect results for the first sample event with detection limits that were high compared to subsequent sample events.

Table 6: Evaluation of Longer-Term (months) Temporal Variability, Altus AFB

Sample Medium	Number of Data Sets (1)	Average Coeff. of Variation (CV)
ABOVE-GROUND AIR		
Ambient Air	0	N/A
Indoor Air	0	N/A
SUBSURFACE GAS		
Subslab	6	1.02
Soil Gas	10	0.80
Well Headspace	5	0.96
GROUNDWATER		
Groundwater	6	0.52

Note: 1) Each data set consists of three chemical concentration measurements (TCE or PCE) with at least two detects from each sample point sampled during each of three sampling events. Number of data sets is different for each medium due to differences in frequency of VOC detection. Data sets with elevated detection limits for non-detect results were not included.

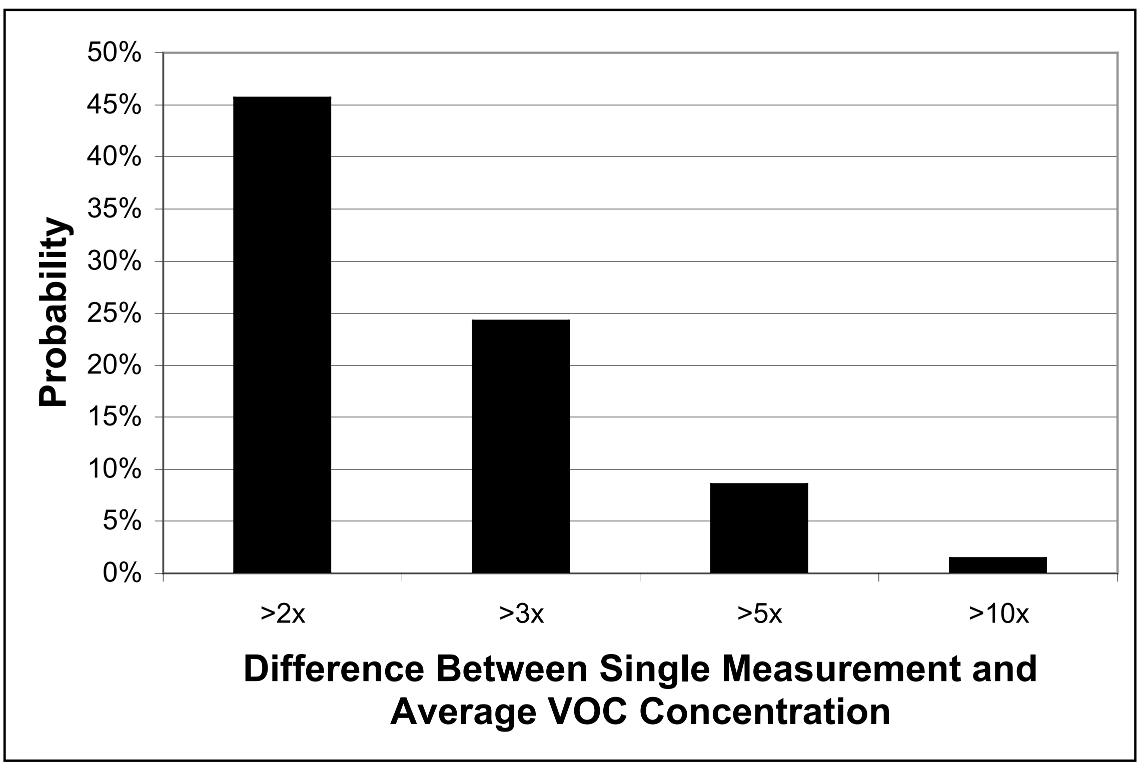
The analysis of longer-term temporal variability at the Altus AFB site indicates that for subsurface gas samples, temporal variability on the time scale of months is similar to spatial variability.

DISCUSSION

Accounting for Spatial and Temporal Variability in Vapor Intrusion Investigations

Understanding the spatial and temporal variability in VOC concentration within each environmental medium is important for planning an effective vapor intrusion investigation program. The risk associated with exposure to environmental chemicals is directly proportional to the average (i.e., arithmetic mean) concentration in the exposure medium[2]. For environmental media that exhibit high spatial or temporal variability in VOC concentration, the VOC concentration measured in a single sample will often differ significantly from the average concentration in that medium resulting in significant uncertainty if that single measurement is used to evaluate risk. For example, Figure 1 show the probability a single VOC measurement will differ from the average VOC concentration by a specified magnitude for an environmental medium where the VOC concentration is log-normally distributed with a CV of 1.

Figure 2: Likely Error Between a Single Measurement and the Average Concentration in a population with a Log-Normal Distribution and a Coefficient of Variation of 1.



If spatial or temporal variability in VOC distribution is known or can be estimated, then we can calculate the number of samples required to estimate the average VOC concentration in an environmental medium with a specified level of accuracy. For example, assuming a normal distribution, the number of samples required to achieve a specified level of accuracy in the estimate of the mean can be calculated as follows:

$$n = [(z \times CV)/E]^2$$

Where

n = The number of samples required

z = The z statistic. The value of the z statistic is based on the specified confidence (or probability) that the sample average will be equal to the population average within the specified fractional error. (The z statistic is 1.96 for 95% confidence, 1.64 for 90% confidence, or 1.15 for 75% confidence)

CV = The population coefficient of variation

E = The fractions error in the estimate of the mean (i.e. 0.5 to estimate the mean within +/- 50%)

Although this calculation is based on an assumption of a normal distribution in VOC concentration, the number of samples required is similar for population with a log-normal distribution but the same CV. Based on the spatial variability and long-term temporal variability in VOC concentrations measured during our study, we have calculated the number of spatially separated sample points required to estimate the average VOC concentration in a medium with a 90% chance of achieving a specified level of accuracy (i.e., +/- 50% and +/- 67%). In addition, we have calculated the number of temporally separated samples from a single sample point required to estimate the long-term average VOC concentration at that sample point with the same levels of confidence and accuracy. The results of these calculations are presented in Table 7.

Table 7: Number of Samples Required to Estimate Average VOC Concentration

	Spatially-Separated Sample Points		**Temporally-Separated Samples from the Same Point**	
Sample Medium	**Number of Points to Estimate Mean +/- 50%**	**Number of Points to Estimate Mean +/- 67%**	**Number of Samples to Estimate Mean +/- 50%**	**Number of Samples to Estimate Mean +/- 67%**
Ambient Air	3	2	NC	NC
Indoor Air	1	1	NC	NC
Subslab	10	6	11	6
Soil Gas	10	6	7	4
Well Headspace	9	5	10	6
Groundwater	9	5	3	2

Note: Based on the observed average coefficient of variation in the environmental medium from the Hill AFB and Altus AFB datasets, this is the number of samples required to achieve a sample mean that is equal to the population mean +/- 50% or +/- 67% for 90% of the sample events. Number of samples required (n) = $[(1.64*CV)/Error]^2$. NC = Not calculated due to insufficient data.

As shown in Table 7, many more samples are required to accurately characterize VOC concentrations in subsurface media compared to above-ground media. For example, six sub-slab sample points are required to estimate the average sub-slab VOC concentration with an error of less than 67% for 90% of sample events. In contrast, only a single indoor air sample will achieve the same level of accuracy. The analysis presented in Table 7, however, is based on the observed variability at two sites. A larger number of samples would be required to characterized indoor or ambient VOC concentrations at sites with higher indoor or ambient spatial variability. Specifically, larger buildings with multiple HVAC systems or air flow zones may exhibit higher levels of spatial variability in indoor air VOC concentrations.

For the subsurface vadose zone, the number of samples required to accurately estimate the long-term average VOC concentration at a single sample point is approximately the same as the number sample points required to accurately estimate the average VOC concentration in a medium during a single sampling event. Based on this understanding, an investigation program of VOCs in subsurface gas should be balanced between spatially and temporally separated samples. For example, a plan to collect nine subsurface gas samples might be implemented by installing three spatially separated sample points and conducting three sampling events temporally spaced over one year.

For groundwater samples at Altus AFB, the longer-term temporal variability was much lower than the spatial variability (CV = 0.52 vs. 1.35). Based on the observed variability, only 3 temporally-separated samples would be required to estimate the mean VOC concentration at that point within 50% but 20 spatially-separated samples would be required to achieve the same level of accuracy in the mean VOC concentration for the medium. As discussed above, most of the groundwater sampling points at the Altus AFB site were screened within the saturated confining layer present above the shallowest transmissive zone. The characterization of variability within this confining layer suggests that when collecting groundwater samples from within such a layer, spatially separated samples provide more information about the variability in chemical distribution than temporally separated samples.

Impact of Variability in VOC Concentration on Measured Attenuation Factors

Attenuation factors, the ratio of indoor air to subsurface VOC concentration, have been widely used by the USEPA and others to characterize vapor intrusion at corrective action sites[8]. Upper-bound attenuation factors have, in turn, been used to develop subsurface VOC concentration screening values considered protective against vapor intrusion impacts (USEPA, 2002). For this purpose, the USEPA has developed a database of attenuation factors measured at corrective action sites where vapor intrusion has been evaluated. After attempting to correct for the influence of background indoor air sources, the USEPA has identified an upper-bound (90^{th} or 95^{th} percentile) attenuation factor and used this attenuation factor to calculate subsurface VOC concentrations that are not expected to cause unacceptable impacts to indoor air. For example, the 2002 USEPA vapor intrusion guidance uses a sub-slab attenuation factor of 0.1. As a result, a sub-slab benzene concentration of less than 31 ug/m^3 would be considered unlikely to cause an indoor air benzene concentration of greater than 3.1 ug/m^3 (i.e., the target indoor air concentration for 10^{-5} risk). The use of a 95th percentile attenuation factor to calculate subsurface screening concentrations is generally interpreted as being conservative (protective) for 95% of buildings. However, if spatial variability in VOC concentration contributes significantly to the variability in the measured attenuation factor, then 95th percentile attenuation factor will be higher than the value needed to protect 95% of buildings.

The attenuation factors in the USEPA vapor intrusion database have been calculated using single paired subsurface and indoor air VOC measurements. Because of spatial variability in VOC concentrations in the subsurface, the attenuation factor calculated based on a single subsurface and a single indoor VOC measurement will vary from the true attenuation for that residence. As a result, the 95th percentile attenuation factor from a database of single paired subsurface and indoor air measurements will reflect both i) the error between the measured attenuation factor and the actual attenuation factor for each building due variability on VOC concentration and ii) the actual variability in VOC attenuation between buildings. The added variability associated with the error between the measured attenuation factor and the true attenuation factor for each building results in a 95th percentile attenuation factor higher than needed to be protective for 95% of buildings.

To better understand the impact of variability in VOC concentrations on attenuation factors, we used a Monte Carlo approach to simulate the measurement of attenuations factors. For this purpose, we assumed log-normal distribution of VOC concentrations in the subsurface gas with a coefficient of variation of 1.0 and a log-normal distribution of VOC concentration in indoor air with a coefficient of variation of 0.25. The average subsurface VOC concentration was set as 1000 times the average indoor concentration, so that the average true attenuation factor would be 0.001. We then generated 5,000 attenuation factors based on simulated measurements from these populations. The resulting average and upper-percentile attenuation factors are shown in Table 8.

Table 8: Distribution of Measured Attenuation For a Building with a True Attenuation Factor of 0.001, Assuming Log-Normal Spatial Variability

Sampling Scheme	**Attenuation Factor (Error) from 5,000 Iterations**			
	Median	**Average**	**90th Percentile**	**95th Percentile**
1 Subsurface / 1 Indoor Air Measurement	0.0014 (1.4x)	0.0022 (2.2x)	0.0044 (4.4x)	0.0062 (6.2x)
3 Subsurface / 3 Indoor Air Measurements	0.0012 (1.2x)	0.0014 (1.4x)	0.0023 (2.3x)	0.0029 (2.9x)
5 Subsurface / 1 Indoor Air Measurements	0.0011 (1.1x)	0.0012 (1.2x)	0.0020 (2.0x)	0.0024 (2.4x)

The Monte Carlo simulation indicates that the variability in VOC concentration will result in a 95^{th} percentile attenuation factor that is 6.2 times higher than the true attenuation factor in a database of attenuation factors based on single subsurface gas and indoor air measurements. It is interesting to note that for assumed log-normal distributions, even average measured attenuation factor is 2.2 times higher than the true attenuation factor for this sampling scheme. The simulation further indicates that the use of multiple measurements to calculate the attenuation factor will reduce the impact of variability on the upper-percentile attenuation factors. The 95^{th} percentile attenuation factors calculated from three subsurface and three indoor air measurements is only 2.9x higher than the true value. Because the variability in the subsurface is higher than the variability in indoor air, a sampling scheme of five subsurface and one indoor air measurement yields a 95^{th} percentile attenuation factor only 2.4x higher than the true value.

The Monte Carlo simulation confirms that spatial variability in VOC concentration can have a large impact on the upper-bound attenuation factor in a database compiled using single paired subsurface and indoor measurements. In the absence of any variation in attenuation between buildings, spatial variability can result in a 95^{th} percentile attenuation factor more than 6 times the true value. However, the use of multiple measurements to calculate the attenuation factor can significantly reduce the impact of spatial variability. This evaluation suggests that all available data should be used to develop a single attenuation factor for each building evaluated rather than calculating an attenuation factor for each single paired measurement.

Summary

As part of three-year study to better understand the site-specific factors that contribute to vapor intrusion impacts, we have characterized the spatial and temporal variability in VOC distribution in subsurface and above-ground environmental media around three buildings located in Oklahoma and Utah. We found that spatial variability in subsurface media (i.e., sub-slab, soil gas, well headspace, and groundwater) was much higher than in above-ground media (i.e., indoor and ambient air). Although short-term (i.e., days) temporal variability was low, longer-term (i.e., months) temporal variability in subsurface media was similar in magnitude to spatial variability. These results indicate that both multiple sample locations and multiple sampling events are needed to accurately characterize average VOC concentrations in subsurface media. Understanding the spatial and temporal variability in VOC concentration is important for planning an efficient and effective vapor intrusion investigation program.

We have used the observed variability on VOC concentration at our study sites to evaluate the utility of the USEPA's attenuation factor approach for the development of subsurface screening values for evaluation of vapor intrusion. Our analysis indicates that spatial variability can result in a 95^{th} percentile attenuation factor more than 6 times higher than the true attenuation factor for an individual building. As a result, the 95^{th} percentile attenuation factors selected by the USEPA are likely to be significantly more conservative than would be expected if the impact of spatial variability were better controlled. The calculation of attenuation factors based on multiple VOC measurements can significantly reduce the impact of variability on the 95th percentile attenuation factor.

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