Recommendations for the Investigation of Vapor Intrusion

ESTCP Project ER-0423

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(ESTCP)

RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

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Acronyms and Abbreviations

COC	constituent of concern
1,1-dfa	1,1-difluoroethane
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
NHDES	New Hampshire Department of Environmental Services
NJDEP	New Jersey Department of Environmental Protection
NYDOH	New York Department of Health
PCE	tetrachloroethene
SF_6	hexafluoride
TCE	trichloroethene
VOC	volatile organic compound

1. INTRODUCTION

1.1 Current Methods for Investigation of Vapor Intrusion Impacts

Since 2000, regulators and the regulated community have become increasingly concerned about the potential for exposure to volatile organic compounds (VOCs) through vapor intrusion to indoor air at sites with contaminated soil or groundwater. Detailed investigations at a limited number of corrective action sites have documented elevated levels of chlorinated VOCs in houses located above contaminated groundwater (DiGiulio et al., 2006; Tillman and Weaver, 2005). In response, the U.S. Environmental Protection Agency (EPA) and many state regulatory agencies have issued guidance specifying screening and field investigation procedures for the identification of vapor intrusion impacts at corrective action sites. Although the specific recommended investigation procedures vary significantly between guidance documents, the majority of these documents utilize a step-wise evaluation process that includes preliminary screening followed by field investigation, if needed. Of the available regulatory guidance on vapor intrusion, the EPA guidance (U.S. EPA, 2002) is currently most widely applied. This guidance document has been formally adopted by some states (e.g., Ohio) and is also widely used in states that have not issued their own guidance documents. The U.S. EPA Vapor Intrusion Guidance recommends the following step-wise evaluation approach:

> Presence of Volatile Chemicals: Vapor intrusion is a potential concern at sites with soil or groundwater impacted by volatile chemicals. Corrective action sites without volatile chemicals (typically defined by vapor pressure and/or Henry's Law constant) require no further evaluation for vapor intrusion. Example volatility criteria are as follows:
>
> - U.S. EPA (2002): Volatile chemicals are defined based on Henry's Law Constant of greater than 1 x 10^{-5} atm-m^3/mol.
> - New Jersey Department of Environmental Protection (NJDEP) (2005): Volatile chemicals are defined based on Henry's Law Constant of greater than 1 x 10^{-5} atm-m^3/mol and a vapor pressure of greater than 1 mm Hg.
>
> Pathway Screening Criteria: For sites with volatile chemicals in soil or groundwater, most regulatory guidance provides conservative screening criteria for preliminary evaluation of the vapor intrusion pathway. Screening criteria are typically provided for groundwater and soil gas and less commonly for soil. These screening criteria are typically used to evaluate whether VOCs are migrating away from a source area at concentrations that could cause a vapor intrusion impact. Although an exceedance of these screening criteria does not indicate that a vapor intrusion impact has occurred or will occur, if the maximum VOC concentration is less than the screening value, then no further evaluation of the vapor intrusion pathway is required. However, for some common constituents of concern (COCs), the EPA screening criteria for groundwater are equal to drinking water standards. In addition, some soil gas screening criteria are less

than or equal to analytical detection limits. As a result, many corrective action sites are not screened from further evaluation using these criteria.

Building-Specific Evaluation: For sites with volatile chemicals present at concentrations above the screening criteria, most guidance documents require a field investigation to determine the presence or absence of vapor intrusion impacts to near-by buildings (commonly defined as within 100 ft of VOC impacts). When conducting a site-specific field investigation, the EPA guidance recommends collection of below foundation (i.e., sub-slab) gas samples followed by simultaneous below foundation and indoor air samples if needed. The EPA guidance raises a number of data quality issues to be addressed as part of the field investigation including: indoor sources of VOCs (background), spatial variability, temporal variability, and duplicate variability. However, the guidance document does not provide a clear recommendation on the amount of data needed to account for these sources of variability and to make a definitive determination of the presence or absence of a vapor intrusion impact. In the absence of clear guidance on the scope of the field investigation, the investigation approaches adopted by individual investigators have varied widely. As a result, disagreements may arise between parties involved at a site regarding the adequacy of a field investigation at a specific building.

Although most state vapor intrusion guidance documents utilize a step-wise investigation approach similar to the USEPA guidance, there are significant differences in exit criteria and pathway screening values. For example, groundwater-screening concentrations for common VOCs can vary by more than 1000x:

Table 1. Groundwater Screening Concentrations for Evaluation of Vapor Intrusion (Residential)

Chemical	**State or Federal Screening Conc. (mg/L)**			
	USEPA	**New Jersey**	**New Hampshire**	**Pennsylvania**
Benzene	0.014	0.015	2.0	3.5
TCE	0.005	0.001	0.05	14
PCE	0.011	0.001	0.05	42

Note: USEPA values based on 10^{-5} cancer risk limit.

In addition, some states (e.g., New York) do not allow screening based on subsurface VOC concentrations, but instead require indoor air testing at all field investigation sites (New York Department of Health [NYDOH], 2005). Overall, vapor intrusion guidance is evolving rapidly. Most states with vapor intrusion guidance have issued new or revised guidance documents within the last three years. The regulatory requirements for the evaluation of vapor intrusion are likely to continue to evolve in the near future with requirements becoming more stringent in some states and less stringent in other states.

1.2 Scope of Document

Currently available vapor intrusion regulatory guidance leaves the investigator with a number of potential questions concerning implementation of a field investigation. Key questions include:

> Collection of Groundwater and Soil Gas Samples: How should groundwater and soil gas samples be collected to generate data suitable for pathway screening?
>
> Identification of Indoor Air Impacts: What field investigation program will provide a cost-effective and timely evaluation of the presence or absence of vapor intrusion impacts?

In this report, the term "*vapor intrusion impact*" is used to describe the presence of a vapor intrusion condition that requires a response action due to an exceedance of applicable regulatory screening levels. The meaning of the term "*vapor intrusion impact*" is intended to be similar to the terms soil impact or groundwater impact which are commonly used to describe exceedances of regulatory standards at corrective action sites. The indoor VOC concentration requiring a response action is typically established by the applicable regulatory authority and may be based on considerations of risk, background, and/or analytical detection limits. Although risk-based concentrations are typically based on chronic exposure, many regulatory authorities require a response action to address any measured exceedances of these concentrations, including short-term exceedances. Because COCs in indoor air may originate from sources other than vapor intrusion, the detection of COCs in indoor air at concentrations above a regulatory standard is not sufficient to define a vapor intrusion impact in all cases and additional evaluation may be required to determine the sources of COCs in indoor air.

Although some state guidance documents establish specific requirements for placement of sample points and define specific methods for collection of samples, the USEPA guidance and most states rely on the investigator to use professional judgment to develop an appropriate vapor intrusion investigation program. In this white paper, we use the results from the Environmental Security Technology Certification Program (ESTCP) project no. ER-0423 to provide recommendations for field investigations of the vapor intrusion pathway at corrective action sites. We provide recommendations to address the two questions identified above. The purpose of these recommendations is to outline a cost-effective approach to the field investigation of the vapor intrusion pathway that is likely to provide a clear determination of the presence or absence of vapor intrusion impacts at the site.

2. SAMPLE COLLECTION METHODS

Under EPA guidance, groundwater and soil gas concentrations can be compared to published screening values to identify sites at which no further evaluation of vapor intrusion is required. The purpose of this section is to discuss the placement of sample points and collection of samples for use in pathway screening. We do not to provide a comprehensive manual on field sampling methods, but instead provide recommendations specific to the collection of groundwater or soil gas samples for the purpose of vapor intrusion pathway screening.

2.1 Groundwater Samples

2.1.1 Placement of Sample Points

In order for a groundwater plume to pose a potential vapor intrusion threat, VOCs must be able to diffuse from groundwater to vadose zone soil gas across the top of the water table. Because diffusion through groundwater is very slow, only VOCs present near the top of the water table pose a potential vapor intrusion threat. A variety of factors can contribute to VOC concentrations at the top of the water table that are lower than those found at greater depth (Nichols and Roth, 2006). In other cases, VOC concentrations at the top of the water table may be higher than those found at depth. As a result, the top of the water table should be targeted when collecting groundwater samples for vapor intrusion screening. Typically, monitoring wells with 10 ft screens are used for delineation and long-term monitoring of groundwater plumes. However, researchers have found that the majority of traditional monitoring wells with longer screens have vertical flow of water within the well (Elci et al., 2001), making it difficult or impossible to obtain a depth discrete groundwater sample from such a well. As a result, smaller screened intervals (1 to 2 ft) are more appropriate for the evaluation of vapor intrusion.

> Study Findings: At both Altus AFB and Hill AFB, monitoring wells with 1 ft screen intervals placed at the top of the water table exhibited VOC concentrations markedly different than near-by wells with 10 ft screens extending deeper in the groundwater-bearing unit. At Hill AFB, the 1 ft screened monitoring wells at the top of the water table exhibited TCE concentrations approximately 3 to 20 times lower than those measured at near-by wells with 10 ft screens (GSI, 2006), however, at Altus, the 1ft screened monitoring well at the top of the water-bearing unit exhibited TCE concentrations approximately 2 to 20 times higher than those measured at near-by wells with 10 ft screens placed deeper in the groundwater-bearing unit (GSI, 2005). At Altus, the shallow groundwater-bearing unit is confined, limiting recharge and potentially creating other factors resulting in high VOC concentrations near the top of the water-bearing unit. However, in both study sites, the difference in VOC concentration between 1 ft screen wells and 10 ft screen wells illustrates the importance of short screen lengths placed at the top of the water-bearing unit for the evaluation of the vapor intrusion pathway.
>
> Recommendation: Groundwater samples used for screening the vapor intrusion pathway should be collected from monitoring wells with short screens (≤ 2 ft) placed at the top of

> the water table. At some sites, a cluster of vertically spaced wells will be required to account for temporal fluctuation in water table elevation and ensure that samples from the top of the water table can be collected during all sampling events.

2.1.2 Sample Collection Methods

No special groundwater sampling methods are required to obtain samples for evaluation of vapor intrusion. Standard methods for sampling and analysis of groundwater for VOCs should be used.

2.2 Soil Gas Samples

2.2.1 Placement of Sample Points

A soil gas sample point is a temporary or permanent location within the vadose zone soils from which a soil gas sample is collected. Although a variety of methods have been used for the installation of soil gas sampling points, a comprehensive comparison of these methods is not available. The choice between temporary or permanent sample points should be made considering the potential need to collect multiple samples over time from the same location.

Samples from soil gas sample points may be used for either pathway screening or evaluation of potential vapor intrusion impacts. When used for pathway screening (i.e., to evaluate whether VOCs are migrating from the source into soil gas), the sample points should be placed in close proximity to the source. For groundwater sources, the sample points should be placed in close proximity to the water table (unconfined conditions) or directly above the confining unit (confined conditions). For soil sources, the sample point should be placed at the edge of the soil source area closest to the potentially impacted building. For evaluation of potential vapor intrusion impacts (i.e., to evaluate the migration of VOCs from soil gas into buildings), the sample points should be placed in close proximity to the potentially impacted building, typically installed through the building foundation.

> Study Findings: For the building-specific evaluation of potential vapor intrusion impacts, collecting soil gas samples adjacent to the building rather than below the building foundation eliminates the difficulty of obtaining access to the inside of the building. However, there is significant uncertainty regarding whether samples collected adjacent to a building are representative of chemical concentrations below the building. At two of the three test buildings evaluated, shallow soil gas VOC concentrations below the building were higher compared to VOC concentrations in soil gas adjacent to the building. At the third building, shallow soil gas VOC concentrations were highest at one of the two sample clusters completed adjacent to the test building. The dataset obtained was not sufficient to determine whether this observed variability between below building and adjacent sample points was higher than or similar to, the general spatial variability observed in soil gas VOC concentration.

> Recommendation: Based on the uncertainty concerning the reliability of samples collected adjacent to a potentially impacted building, below foundation samples should

be used for the collection of soil gas samples used to evaluate potential building-specific vapor intrusion impacts.

2.2.2 Sample Purge Volume

Prior to sampling a soil gas point, the point and associated sample line must be purged to remove gas within the sample point and line that may not be representative of subsurface VOC concentrations. The purge volume should be sufficient to thoroughly flush the sample point and line but should minimize the disturbance of subsurface gas so that the sample collected is representative of the immediate vicinity of the sample point.

Study Findings: At each of the two demonstration sites, a purge study was conducted to determine the effect of increasing purge volumes on sample VOC concentrations. For the points tested, samples were collected following purges of 1 to 8 line volumes (i.e., the volume of the sample point and associated tubing). The COC concentrations measured in the samples typically increased between purges of 1 and 2 line volumes and were generally stable between 2 to 8 line volumes. COC concentrations were most stable in the sample points with the lowest total line volumes, but were somewhat more variable for sample points with larger line volumes. These results indicating stable VOC concentrations over a broad range of sample line purge volume are similar to those reported by other investigators at the Raymark Superfund site (DiGiulio et al., 2006) and Cody, Wyoming site (McAlary and Creamer, 2006) and indicate that vapor intrusion investigation results are unlikely to be distorted by minor variations in soil gas sample collection methods.

Recommendation: A purge volume equal to 3 line volumes should be used to ensure thorough flushing of the sample collection line but minimize the flow of gas in the subsurface around the sample collection point induced by the purging process. Required purge volumes should be minimized by using sample tubing with a small inside diameter such as 1/8th inch Nylaflow™ tubing (line volume = 1 mL/ft).

2.2.3 Soil Gas Sample Leak Tracers

Leaks around sample collection points, or in sample lines, can result in samples that are not representative of actual VOC concentrations at the sample point. Unlike soil or water samples, it is difficult to ensure that a gas sample originated from the location of the sample point. Ambient air may enter the sample container through leaks in the sample lines or around the sample point casing. Vacuum testing of the sample lines can be used to demonstrate an absence of line leaks, and leak tracer compounds can be used to evaluate the integrity of both the sample point casing and the sample line.

Study Findings: During the study, a combination of vacuum testing and leak tracer compounds were used to evaluate the integrity of soil gas sample point casings and sample lines. If leak tracer compound was detected in a soil gas sample, the magnitude of the leak was estimated by comparing the concentration of leak tracer in the sample to the concentration released around the sample point (approximately 5% by volume).

When leak tracers are used during sample collection, it is common to find detectable concentrations of leak tracer in the soil gas sample (Personal communication from Matt Lavis of Shell and Todd McAlary of Geosyntec), and therefore, leakage rates of less than 1% were not considered significant. However, during some sample events, the presence of leak tracer compound in the soil gas samples indicated leakage rates between 1% and 10% for some samples. Application of a fresh bentonite seal around the top of the sample point casing prior to sample collection reduced the concentration of leak tracer in the sample, indicating that the leakage was primarily around the sample point casing and not through the sample lines.

During one sample event, the leak tracer itself caused significant problems. During this sample event, 1,1-difluoroethane (1,1-dfa, the propellant in duster spray) was used as the leak tracer. In several samples, 1,1-dfa in the soil gas samples at concentrations indicating a leakage rate of less than 1% resulted in elevated detection limits for the target VOCs, resulting in a failure to meet the data quality objective for detection limits in these samples. For subsequent sampling events, sulfur hexafluoride (SF_6), a compound that does not cause interference with the detection of VOCs by TO-15, was used as the leak tracer compound. USEPA method TO-15 is the most commonly used method for analysis of VOC concentrations in air and soil gas samples.

Recommendation: A combination of vacuum testing of lines and leak tracers should be used to ensure the integrity of soil gas samples. Above-ground sample lines should be vacuum tested for tightness prior to sample collection and a leak tracer compound should be released around the sample point casing during sample collection. Common leak tracer compounds include pentane, isopropyl alcohol, helium, and SF_6. The selection of the leak tracer compound should be coordinated with the analytical laboratory to ensure that its presence in soil gas samples will not interfere with the analysis of target compounds. If leak tracer compound is detected in the soil gas sample, then the leakage rate should be estimated and corrective action implemented as follows:

Leakage Rate (by volume)	**Corrective Action**
<1%	None. Leakage is not significant
1% to 10%	Reduce leakage for future sampling events. Sample results should be considered valid, but the source of leakage should be identified and controlled during future sampling events.
>10%	Reject results and resample. Analytical results may not be representative of actual COC concentrations in soil gas at the sample point. Resample these points using improved sample collection methods to reduce leakage.

2.2.4 Sample Containers

Summa canisters are the most commonly used containers for the collection of soil gas or air samples for off-site analysis of VOCs. These canisters are typically provided by the laboratory and are reused many times. As a result, care must be taken to prevent carry-over contamination between sample events. TO-15 analytical procedures require batch certification of Summa canisters following cleaning (i.e., testing of one canister per 20 to ensure an absence of contamination). Most laboratories will provide individual clean certification (i.e., testing of all canisters following cleaning) for an additional charge of approximately $75 per canister.

Summa canisters are typically available in 6L and 1L sizes, with 400 mL canisters available from some laboratories. 6L canisters are typically used for collection of indoor and ambient air samples because the larger volume supports easy collection of 8 or 24 hr samples using flow controllers. 1L or smaller canisters are typically used for collection of soil gas samples in order to minimize the induction of soil gas flow and to reduce the potential for air flow from the ground surface into the sample. In order to further reduce the required soil gas sample volume, 1L summa canisters can be partly filled with inert gas by the laboratory prior to use. Some laboratories require significantly less than 1L of gas in order to achieve standard TO-15 detection limits, however, the specific sample volume required should be verified with the laboratory.

> Study Findings: During the project, one batch of analytical results was rejected due to problems with carry-over contamination in the Summa canisters despite batch certification. Other researchers have reported similar problems, although the prevalence of carry-over contamination in batch certified Summa canisters is not known and likely varies between laboratories. Individually certified clean Summa canisters and flow controllers were used for subsequent sampling events and no further evidence of carry-over contamination was noted.
>
> Recommendation: Individually certified clean Summa canisters should be requested when Summa canisters are used for VOC analysis of soil gas or air. 1L or smaller Summa canisters should be used for the collection of soil gas samples in order to minimize the volume of soil gas drawn through the sample point.
>
> Recent research indicates that Tedlar bags are a suitable alternative to Summa canisters for VOCs when the holding time is less than two weeks (Paul, 2007); however, some regulators may not accept results for samples collected in Tedlar bags. For larger field programs, use of an on-site mobile laboratory may be a cost-effective alternative to off-site analysis. When using an on-site laboratory, gas samples may be collected in either Tedlar bags or gas-tight syringes.

3. RECOMMENDED APPROACH FOR BUILDING-SPECIFIC INVESTIGATION OF VAPOR INTRUSION

As discussed in Section 1, most available regulatory guidance recommends a step-wise approach for the evaluation of potential vapor intrusion sites based on COC screening, pathway screening, and receptor evaluation. Because a single source area has the potential to impact multiple receptors, this step-wise approach will generally be the most efficient and cost-effective for the evaluation of vapor intrusion. Regulatory guidance should be consulted for appropriate COC and pathway screening procedures.

For sites where COC screening and pathway screening indicate COCs may be migrating from a local source through soil gas towards a building or buildings, a field investigation is required to determine the presence or absence of vapor intrusion impacts to these specific buildings. In this section, we provide our recommendation for a cost-effective field investigation program that is likely to provide a reliable determination of the presence or absence of a vapor intrusion impact. The investigator should keep in mind that i) applicable regulatory guidance may impose additional or different investigation requirements and ii) the understanding of vapor intrusion is evolving rapidly and recommended investigation approaches are likely to continue to evolve.

3.1 Building-Specific Vapor Intrusion Screening

A building-specific field investigation is typically recommended when VOC concentrations collected in close proximity to the source (i.e., in deep soil gas or shallow groundwater) exceed conservative screening concentrations. However, prior to a detailed evaluation of the target building, the investigator should conduct receptor screening by comparing VOC concentrations in indoor air, or below the building foundation, to conservative screening concentrations. The decision on whether to conduct screening sampling of indoor air or below foundation soil gas will be building specific and may include the following considerations:

> Indoor Sources: Are indoor sources of VOCs likely to contribute to measured VOC concentrations in indoor air?
>
> Building Access: Will building occupants allow penetration of the building foundation for the collection of below-foundation gas samples?
>
> Regulatory Requirements: Do applicable regulations or guidance specifically require the use of indoor or below-foundation samples for screening?

For a typical single-family residential building, one indoor air sample or three below-foundation soil gas samples should be collected. A larger number of samples are required for screening based on below-foundation VOC concentration due to the higher spatial variability in the distribution of VOCs within soil gas. If VOC concentrations are non-detect or below conservative screening concentrations, then no further immediate evaluation of vapor intrusion is required for the building. However, additional follow-up monitoring may be warranted at some buildings to evaluate the potential for intermittent vapor intrusion impacts to occur at other times. If VOC concentrations are above conservative screening concentrations, then additional evaluation of the building should be conducted. Because VOCs present below the building foundation may originate from inside the building or from ambient sources, caution should be used in the interpretation of sample results indicating the presence of low VOC concentrations below the building foundation (McHugh et al., 2006).

3.2 Building-Specific Vapor Intrusion Evaluation

For buildings with VOCs present in or below the building at concentrations above conservative screening levels, the following comprehensive sampling program is likely to provide a clear determination of the presence or absence of a vapor intrusion impact at the target building during the sampling event.

3.2.1 Sample Collection and Analysis Program

In order to understand the origin of any VOCs detected in the target building, samples for VOC and radon analysis should be collected simultaneously from below the building foundation, indoors and outdoors. A recommended typical sampling program is summarized in Table 2. The use of consistent investigation methods between building locations will provide comparable results that serve to provide an increased understanding of vapor intrusion processes over time.

Table 2. Recommended Typical Sample Collection Program for Evaluation of Vapor Intrusion

Environmental Medium	Analyses	Sample Duration	Sample Container	Number of Samples	Sample Locations
Ambient air	VOCs by TO-15[1]	24 hr	6L Summa	1	Upwind
	Radon[2]	Grab	0.5 L Tedlar	1	
Indoor air	VOCs by TO-15[1]	24 hr	6L Summa	1 - 2[3]	Lowest floor
	Radon[2]	Grab	0.5 L Tedlar	1 - 2[3]	
Sub-slab gas	VOCs by TO-15	Grab	0.4L or 1L Summa	3 - 5[3]	Distributed below lowest floor
	Radon[2]	Grab	0.5 L Tedlar	3 - 5[3]	

Note: 1) TO-15 SIM may be required for indoor and ambient air samples to achieve detection limits below regulatory screening values. TO-15 analyses are conducted by numerous commercial laboratories. The TO-15 analyte list may vary between laboratories and should be reviewed to ensure inclusion of all volatile COCs.
2) Radon samples analyzed by Dr. Doug Hammond (dhammond@usc.edu) at the University of Southern California Department of Earth Sciences using the extraction method of Berelson, 1987 and the analysis method of Mathieu, 1998.
3) Recommended number of samples for a typical residence with a 1000 - 2000 ft^2 foundation. Additional samples may be appropriate for larger structures.

Although radon analysis is not generally available from commercial laboratories, Dr. Doug Hammond (dhammond@usc.edu) at the University of Southern California will analyze samples for consultants and other parties. This analysis does not have a defined detection limit; however, measurement accuracy decreases with decreasing radon concentration. The measurement accuracy for a sample containing 0.2 pCi/L radon is estimated to be +/-30% (McHugh et al., 2008). Ambient radon concentrations range from 0.2 to 0.7 pCi/L (EPA, 1993), indicating that ambient radon concentrations can be measured with an accuracy of +/-30% or better. Field duplicate samples analyzed for this project typically showed a relative percent difference of less than 30%, the typical data quality objective for field duplicates. Despite the limited availability of radon analyses, the usefulness of this analyte has been widely recognized by the EPA and many consultants and is specifically recommended by some regulatory guidance (e.g., New Hampshire Department of Environmental Services [NHDES], 2006, Section 8.1).

The recommendation to collect more sub-slab gas samples than indoor air samples is based on the finding that spatial variability in VOC concentration is much higher in subsurface gas than in indoor or ambient air. As a result, a larger number of spatially-separated samples are required from below the building foundation in order to characterize the distribution of VOCs in this medium. Although 1 or 2 indoor air samples will be sufficient to characterize VOC concentrations in this medium, additional targeted indoor air samples should be added, if needed, to characterize the impact of suspected indoor sources that cannot be removed from the building during the sampling event.

3.2.2 Data Evaluation

The identification of vapor intrusion impacts should be based on a weight-of-evidence approach using the following data evaluation methods:

> Indoor Air Data: If indoor VOC concentrations are below indoor screening levels then no further immediate evaluation of vapor intrusion is required. Additional follow-up monitoring may be warranted at some buildings to evaluate the potential for intermittent vapor intrusion impacts to occur at other times.
>
> Evaluation of Potential VOC Sources: If indoor VOC concentrations exceed indoor screening levels, then VOC and radon concentrations should be evaluated to help identify the most likely source or sources of the indoor air impacts.

- *Evidence of Ambient Sources*: Ambient VOC concentrations greater than or similar to indoor VOC concentrations indicate that ambient sources are the likely primary source of VOCs in indoor air.
- *Evidence of Indoor Sources*: Indoor VOC concentrations >10% of below foundation concentration and/or large differences in below foundation to indoor air attenuation factors between VOCs indicate that indoor sources are likely the primary source of one or more of the VOCs in indoor air. For example, a PCE attenuation factor of 0.03 and a trichloroethene (TCE) attenuation factor of 0.001 would suggest a likely indoor source of tetrachloroethene (PCE).
- *Evidence of Vapor Intrusion*: The following factors together indicate that vapor intrusion is likely the primary source of observed indoor air impacts: i) indoor VOC concentrations greater than ambient VOC concentrations, ii) below foundation to indoor air attenuation factors <0.01 and, iii) below

foundation to indoor air attenuation factors similar for all VOCs and for radon.

For buildings where both indoor or ambient sources and vapor intrusion are contributing to the observed indoor air impact, the indoor VOC concentration attributable to vapor intrusion ($C_{ia\text{-}vi}$) can be estimated as:

$$C_{ia\text{-}vi} = C_{sg} \text{ x } AF_{radon}$$

Where C_{sg} is the VOC concentration in soil gas and AF_{radon} is the measured radon attenuation factor i.e., $(radon_{indoor}\text{-}radon_{ambient})/radon_{sub\text{-}slab}$. Using this approach, the contribution of indoor VOC sources can be accounted for and the calculated indoor VOC concentration attributable to vapor intrusion can be compared to regulatory standards for indoor air to determine the need for mitigation of vapor intrusion impacts.

<u>Impact of Variability on Evaluation</u>: Analytical, spatial, and temporal variability in measured VOC concentrations results in some uncertainty regarding the presence or absence of a vapor intrusion impact. If the average measured VOC concentration during a sample event is close to the applicable screening value (e.g., +/- 50%), then additional sampling may be warranted to provide a more definitive determination of the vapor intrusion condition. Section 3.3.2 of this document provides a discussion of cost considerations related to further evaluation or mitigation of potential vapor intrusion impacts. The significance of analytical, spatial, and temporal variability is briefly discussed below:

- *Analytical Variability*: With the exception of occasional false-positive detections, analytical variability is generally low (i.e., RPD between laboratory duplicates of <10%). Unexpected low-concentration detections of VOCs should be confirmed through resampling.
- *Spatial Variability*: Spatial variability in VOC concentrations in indoor air is generally low. As a result, 1 to 2 samples should generally provide an estimate of the true average indoor air concentration within +/- 50%. Additional indoor air samples from a single sample event are unlikely to change the data interpretation. Spatial variability in soil gas (including sub-slab soil gas) is generally much higher with up to 10 samples required to estimate the true average VOC concentration within +/-50%.
- *Temporal Variability*: Temporal variability in indoor VOC concentrations has not been well characterized. As a result, long-term monitoring of indoor VOC concentrations may be warranted when measured concentrations are close to applicable screening values. Temporal variability in soil gas is similar in magnitude to spatial variability. Because of the high spatial and temporal variability in VOC concentration in soil gas, vapor intrusion evaluations based solely or primarily on a small number (i.e., 1-3) of soil gas samples should be considered to provide an order-of-magnitude accuracy.

A more comprehensive discussion of the impact of variability in VOC concentration on the vapor intrusion evaluation is provided in the ESTCP ER-4023 final report.

3.2.3 Optional Additional Evaluation Methods

The following additional field evaluations may provide an improved understanding of vapor intrusion conditions in the building.

Cross-Foundation Pressure Gradient: The pressure gradient across the building foundation largely controls the movement of VOCs and other gases between the shallow soil and the building interior. When the building foundation has cracks or penetrations that support gas flow, gas will flow from the shallow soil into the building during times when the building has a lower pressure than the soil (i.e., negative building pressure) and gas will flow from the building into the shallow soil during times when the building has a higher pressure than the soil (i.e., positive building pressure). A variety of building and meteorological conditions can affect the pressure gradient across the building foundation including: building operating conditions, ambient temperature, wind conditions, changes in barometric pressure, and pressurized gas sources.

Cross-foundation pressure gradient can be measured using a differential pressure transducer with data logger such as the Omniguard 4. These pressure transducers can measure positive and negative pressure gradients, providing an indication of advective forces into and out of the building. The pressure transducer contains 2 pressure ports, one of which is open to the indoor atmosphere and one of which was isolated in the sub-slab atmosphere by tubing extending through the building slab and sealed from the indoor atmosphere.

Cross-foundation pressure gradient measurements can be used to determine the driving force for transport across the building foundation during the sample collection event. The predominant driving force for flow across the building foundation can be determined as follows:

- A consistently high building pressure (i.e., positive building pressure) indicates the potential for airflow from the building to the shallow soils.
- A consistently low building pressure (i.e., negative building pressure) indicates the potential for airflow from the shallow soils into the building.
- A pressure gradient varying between positive and negative building pressures indicates the potential for bi-directional flow between the building and shallow soil gas. Sufficient data should be collected to confidently determine whether the average gradient is positive, negative, or zero.

Note that variations in pressure gradient at different locations within the building may result in some transport in the opposite direction from that suggested by the measured pressure gradient. However, the measured gradient will indicate the predominant direction of flow through the foundation.

Induced Building Depressurization: Temporal variations in cross-foundation pressure gradient may result in temporal variations in the presence and magnitude of vapor intrusion impacts. In other words, the magnitude of vapor intrusion impacts may be highest during periods of sustained negative building pressure. If sampling is conducted only under normal building operating conditions, several sampling events may be required to determine the full range of potential vapor intrusion impacts. However, through the induction of a negative building pressure, building conditions can be created allowing the maximum magnitude of vapor intrusion impact to be evaluated through a single sampling event. Following the collection of baseline samples, a low-pressure condition can be created in the target building through the placement of a box fan in a window blowing out. Following a stabilization period of 6 to 12 hours, the original sampling program can be repeated. The two datasets generated from this program (baseline and depressurization) can be used to evaluate the potential for vapor intrusion impacts over a range of building pressure conditions.

3.3 Evaluation Costs

Costs for the investigation of vapor intrusion have been estimated using typical laboratory costs and assuming that investigations of multiple buildings will be conducted by an experienced team of investigators. Labor hours will likely be higher for personnel without significant experience in vapor intrusion investigations due to the additional time required for project planning and reporting. Similarly, labor hours will likely be higher for the investigation of a single building because planning and reporting tasks cannot be spread between several buildings.

3.3.1 Recommended Vapor Intrusion Investigation Program

Typical unit costs for laboratory analyses and materials are provided in Table 3, typical costs for initial screening are provided in Table 4, and typical costs for comprehensive building evaluation are provided in Table 5.

Table 3. Typical Unit Costs for Vapor Intrusion Analyses

Item	Typical Cost
VOC analysis by TO-15 (Includes Summa can rental for individually certified clean canisters)	$310
VOC analysis by TO-15 SIM (Includes Summa can rental for individually certified clean canisters)	$340
Radon analysis (Includes Tedlar bag for sample collection)	$110
Hammer drill for installation of sub-slab sample points (1 day rental)	$50
Differential pressure transducer/logger (purchase)	$1300
Differential pressure transducer/logger (1 week rental)	$350

Table 4. Typical Costs for Screening of a Single Family Residence

Item		Estimated Cost
Labor:	Project planning - 2 hrs; field program - 4 hrs; analysis and reporting - 4 hrs.	$1,000
Laboratory:	Indoor air - 1 sample for VOC analysis by TO-15 SIM or Sub-slab - 3 samples for VOC analysis by TO-15.	$340 to $930
Materials:	Indoor air - none or Sub-slab - Hammer drill rental	$0 to $50
	Total Costs: Indoor Air Screening	**$1,300**
	Total Costs: Sub-Slab Screening	**$2,000**

Note: Assumed labor costs of $100/hr.

Table 5. Typical Costs for Evaluation of a Single Family Residence

Item		Estimated Cost
Standard Evaluation		
Labor:	Project planning - 8 hrs; field program - 10 hrs; analysis and reporting - 8 hrs.	$2,600
Laboratory:	Ambient air - 1 sample for VOC analysis by TO-15 SIM and 1 sample for radon analysis Indoor air - 2 samples for VOC analysis by TO-15 SIM and 2 samples for radon analysis Sub-slab - 4 samples for VOC analysis by TO-15 and 4 samples for radon analysis	$3,060
Materials:	Hammer drill rental	$50
	Total Costs for Standard Evaluation	**$6,700**
Optional Additional Evaluations		
Building Depressurization: Following collection of baseline samples, induce negative building pressure and repeat field sampling program (10 hrs labor plus sample laboratory program as baseline sampling)		$4,060
Cross-Foundation Pressure Gradient: Measure cross-foundation pressure gradient during field program (1 hr labor plus transducer rental)		$450

Note: Assumed labor costs of $100/hr.

3.3.2 Cost Considerations for Further Monitoring or Mitigation

Depending on the results of a vapor intrusion investigation, additional monitoring or mitigation may be required resulting in additional costs. An initial investigation has three potential outcomes: i) definitive determination of no vapor intrusion impact, ii) definitive determination of the presence of a vapor intrusion impact, of iii) no definitive finding. In the first case, no further investigation or mitigation is required. In the second case, mitigation is required. In the third case, either further monitoring or mitigation is required. Although the installation of a radon-style mitigation system in a single-family residence is not very expensive (typically $2,000 to $4,000), there are additional costs associated with short and long-term monitoring to confirm the effectiveness of the system. New York typically requires only a single round of confirmation sampling to verify mitigation system performance (NYDOH, 2006), however, other states typically require on-going monitoring. Colorado requires initial quarterly sampling that can decrease to annual sampling (David Folks, Personal Communication). Hill AFB in Utah conducts annual confirmation sampling in residences with mitigation systems (Jarrod Case, Personal Communication) and Kansas requires confirmation sampling at a frequency of once every three to four years (Bill Morris, Personal Communication). In each case, monitoring is continued for as long as the vapor intrusion source remains. As a result, installation of a mitigation system to address a potential or confirmed vapor intrusion impact is likely to entail significant long-term monitoring costs.

When the initial investigation of the vapor intrusion pathway does not yield a definitive determination of the presence or absence of a vapor intrusion impact, then the cost of further investigation must be balanced against the cost of mitigation. If the initial investigation indicates that a vapor intrusion impact is unlikely, but the finding is not definitive, then 1 to 3 follow-up sampling events is likely to be sufficient to confirm the initial findings. The likely costs associated with further monitoring can be estimated based on the unit costs provided in Section 3.3.1. If the initial investigation indicates that a vapor intrusion impact is likely, but the finding is not definitive, then longer-term monitoring may be required. In this case, installation of a mitigation system may be the most cost-effective approach because further monitoring is likely to indicate that mitigation is, in fact, required. It should be noted, however, that the installation of a mitigation system at a site where a vapor intrusion problem has not been confirmed may create the perception that an actual vapor intrusion problem existed prior to the installation of the system. This may create concerns regarding exposure prior to installation of the system, or during periods where the system does not operate, and may increase the risk of litigation and third-party claims.

Costs for mitigation monitoring or follow-up sampling will vary widely depending on regulatory and other requirements. However, for a defined sampling program, expected costs can be estimated using the unit costs provided in the tables above.

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