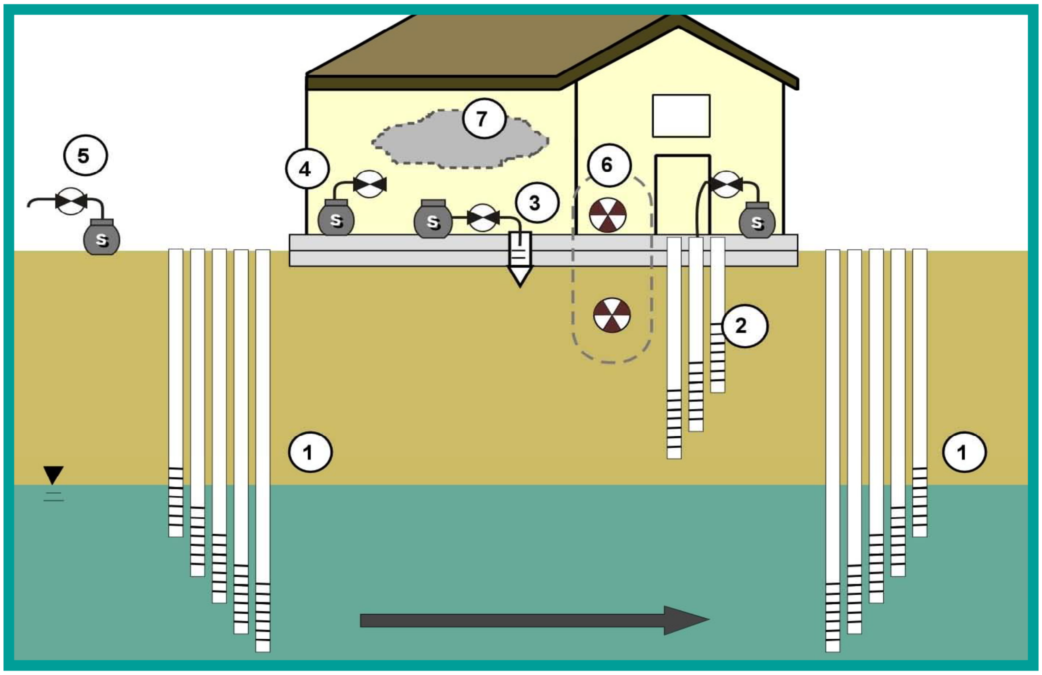
ESTCP
Cost and Performance Report

(ER-0423)



Detailed Field Investigation of Vapor Intrusion Processes

August 2008

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **01 AUG 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Detailed Field Investigation of Vapor Intrusion Processes**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **ESTCP Program Office 901 North Stuart Street Suite 303 Arlington, Virginia 22203**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**45**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

COST & PERFORMANCE REPORT

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
bgs	below ground surface
COC	chemicals of concern
CV	coefficient of variation
1,2-DCE	1,2-dichloroethene
DFA	difluoroethane
DQO	data quality objective
ESTCP	Environmental Security Technology Certification Program
HCl	hydrochloric acid
OU-5	Operable Unit 5
PCE	tetrachloroethene (also called perchloroethene)
PQL	practical quantitation limit
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RFI	remedial field investigation
RPD	relative percent difference
SF_6	sulfur hexafluoride
SG	soil gas
SIM	selective ion monitoring
TCE	trichloroethene
USEPA	U.S. Environmental Protection Agency
VOA	volatile organic analysis
VOC	volatile organic compound

ACKNOWLEDGEMENTS

This project would not have been possible without the support and contribution of numerous individuals and organizations. The authors thank Ivette O'Brien and Samuel Brock of the Air Force Center for Engineering and the Environment (AFCEE) for support and oversight; Kyle Gorder, Jarad Case, Art Whallon, Charles Butchee, and other personnel at Hill Air Force Base (AFB) and Altus AFB for providing access and facilitating implementation of the project at these bases; Blayne Hartman and the staff of H&P Mobile Geochemistry for project support; Doug Hammond of the University of Southern California for analysis of radon concentrations in air and soil gas (SG) samples; Chet Clarke of the Texas Commission on Environmental Quality for review and comment on the project plan; the Environmental Security Technology Certification Program (ESTCP) technical review staff for helpful technical comments and suggestions; and Andrea Leeson and the ESTCP program staff at HydroGeoLogic, Inc. for invaluable project support.

Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The purpose of this demonstration was to validate improved vapor intrusion field investigation methods to support cost-effective evaluation of the vapor intrusion pathway. Intensively monitored sites, such as the Borden Landfill in Canada, have greatly contributed to our understanding of the physical and chemical processes that control the transport of chemicals in groundwater. For this project, we have used a similar approach (i.e., intensively monitored sites with specially designed monitoring networks) to address the critical groundwater-to-indoor-air vapor intrusion pathway.

The primary goal of the project has been to support the development of refined vapor intrusion guidance, stepwise screening, and cost-effective field investigation approaches. This will benefit facility managers by providing investigation results that support a defensible evaluation of vapor intrusion. Determination of the presence or absence of vapor intrusion impacts is important to the site management process. Definitive determination of the absence of vapor intrusion allows resources to be directed to other site impacts while avoiding presumptive mitigation, which can be burdensome from both financial and public relations perspectives.

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objective of this demonstration study was to identify a cost-effective and accurate protocol for investigation of vapor intrusion into buildings overlying contaminated groundwater. Three performance goals were established, and all objectives were met, namely,

- Collection of data representative of site conditions
- Determination of vapor intrusion impacts at demonstration sites (i.e., indoor air concentration of chemical above risk-based screening limit, not attributable to background indoor air sources)
- Development of a reliable vapor intrusion investigation approach (i.e., identify a limited scope investigation approach with higher accuracy than current approaches).

1.3 DEMONSTRATION RESULTS

The results of the demonstration supported the use of a step-wise process for the evaluation of vapor intrusion from groundwater sources. This recommended evaluation process has been documented in a project White Paper (GSI Environmental, 2007). The recommended sampling program when evaluation of individual buildings is required, is summarized in Table 1.

Table 1. Recommended Sample Collection Program for Evaluation of Vapor Intrusion at Individual Buildings.

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

Note:

[1] TO-15 selective ion monitoring (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 chemicals of concerns (COC).

[2] Radon samples analyzed by Dr. Doug Hammond (dhammond@usc.edu) at the University of Southern California Department of Earth Sciences as described in McHugh et al. (2008). Analysis of radon in gas samples is not currently available from commercial environmental laboratories; however, Dr. Hammond will conduct the analysis for environmental consultants and other parties.

[3] Recommended number of samples for a typical residence with a 1,000-2,000 ft^2 foundation. Additional samples may be appropriate for larger structures.

1.4 IMPLEMENTATION ISSUES

Spatial and temporal variability in volatile organic compound (VOC) concentrations has a significant impact on vapor intrusion investigations. High spatial and long-term temporal variability in soil gas (SG) VOC concentration results in high uncertainty associated with VOC transport through the vadose zone. Because of this high variability, a large number of sample locations and sampling events is needed to accurately characterize the VOC distribution in SG.

Other observations and lessons learned concern the sampling and analysis process. Summa canisters are the most commonly used containers for SG or air sample collection. Because these canisters are typically provided by the laboratory and reused many times, care must be taken to prevent cross-contamination between sample events. Another important consideration with SG samples is the use of a leak tracer, important to ensure that the collected sample is not impacted by significant leakage of ambient air. Some leak tracer compounds such as difluoroethane (DFA) and isopropyl alcohol may cause elevated detection limits for target compounds. It is important to confirm with the analytical laboratory that the tracer compound will not interfere with the analysis of target compounds.

The results of the demonstration have been used to develop a recommended approach for cost-effective, building-specific evaluation of vapor intrusion impacts at corrective action sites. It is important to note, however, that the understanding of vapor intrusion is evolving rapidly and that the recommended approach may not satisfy all regulatory requirements. The end user should review applicable guidance and regulations and modify or supplement this approach to ensure that regulatory requirements are satisfied.

2.0 INTRODUCTION

2.1 BACKGROUND

The purpose of this demonstration was to validate improved vapor intrusion field investigation methods to support cost-effective evaluation of the vapor intrusion pathway. Intensively monitored sites, such as the Borden Landfill in Canada, have greatly contributed to our understanding of the physical and chemical processes that control the transport of chemicals in groundwater. For this project, we have used a similar approach (i.e., intensively monitored sites with specially designed monitoring networks) to address the critical groundwater-to-indoor-air vapor intrusion pathway. The performance objectives were met by:

- Collecting a high density of data related to vapor intrusion at the test sites
- Analyzing this data to obtain a thorough understanding of vapor intrusion processes at the test sites
- Utilizing the results to develop a reliable and cost-effective approach for investigation of vapor intrusion at other sites.

2.2 OBJECTIVES OF DEMONSTRATION

The primary objective of this demonstration study was to identify a cost-effective and accurate protocol for investigation of vapor intrusion into buildings overlying contaminated groundwater. Performance objectives are summarized in Table 2.

Table 2. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	1. Collection of data representative of site conditions	Precision, accuracy, completeness, representativeness, and comparability	Objective attained
Quantitative	2. Vapor intrusion impact at demonstration site	Indoor air concentration of COC* above risk-based screening limit and not attributable to background indoor air sources	Objective attained
Qualitative	3. Reliable vapor intrusion investigation approach	Accuracy of vapor intrusion determination as characterized by false positive and false negative rates. Identify limited scope investigation approach with higher accuracy than current approaches such as the USEPA (2002)	Objective attained

* Chemicals of Concern

2.3 REGULATORY DRIVERS

At a limited number of sites in the United States, migration of VOCs from affected groundwater via vapor phase diffusion has impacted indoor air quality in overlying structures, posing a potentially significant yet previously unrecognized human health concern for such properties. To address this concern, the U.S. Environmental Protection Agency (USEPA) has issued the "Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils" (USEPA, 2002), providing conservative screening limit concentrations for various VOCs in groundwater. The high level of conservatism in the USEPA and state guidance reflects the current limitations of our understanding of the physical and chemical processes that contribute to vapor intrusion. A primary goal of this project has been to support the development of refined vapor intrusion guidance based on an improved understanding of the site-specific factors that influence vapor intrusion.

2.4 STAKEHOLDER/END-USER ISSUES

The USEPA Vapor Intrusion Guidance and many state guidance documents recommend a step-wise approach for the evaluation of vapor intrusion involving application of: 1) volatile chemical screening, 2) concentration-based pathway screening, and 3) building-specific evaluation. The results of this demonstration have been used to develop a recommended approach for the cost-effective, building-specific evaluation of vapor intrusion impacts at corrective action sites. Although the understanding of vapor intrusion processes is still evolving, the investigation approach has been developed to provide a reliable and cost-effective determination of the presence or absence of vapor intrusion impacts at buildings overlying VOCs in groundwater or soil. The step-wise screening and field investigation approach will benefit facility managers by providing investigation results that support a defensible evaluation of vapor intrusion.

3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Although the scientific and regulatory communities have been aware of the subsurface-to-indoor air vapor intrusion pathway for over two decades, awareness of this pathway as a potentially significant contributor to human exposure at VOC-contaminated sites has increased dramatically in the last 7 years. The evaluation of the vapor intrusion pathway has evolved as follows:

- **1980s**: The study of vapor intrusion focuses primarily on radon and landfill gas (Altshuler and Burmaster, 1997; Richardson, 1997; Folkes and Arell, 2003). Due to the uncertainty associated with modeling of radon intrusion into houses, the USEPA recommends direct measurement of radon in place of modeling (USEPA 2004).
- **1990s**: The potential for vapor intrusion impacts at VOC-contaminated sites is primarily evaluated through the use of modeling. The Johnson-Ettinger model (Johnson and Ettinger, 1991) extended some of the assumptions originally employed in radon vapor intrusion models to represent diffusive and pressure-driven (i.e., advective) transport of VOCs from a subsurface vapor source to indoor air. In the mid-nineties, several state regulatory agencies and the USEPA (USEPA, 2000) applied the Johnson-Ettinger model, together with conservative assumptions, to develop risk-based groundwater screening levels that would be protective of human exposure to indoor air impacted by vapor intrusion.
- **2000s**: The USEPA issues draft guidance for the evaluation of vapor intrusion at VOC-contaminated sites (USEPA, 2001; USEPA, 2002). USEPA guidance limits the use of models for the evaluation of vapor intrusion and instead recommends the use of conservative screening concentrations and field measurements of vapor intrusion. Numerous states issue guidance documents, many recommending a screening approach similar to the USEPA process.

Although the USEPA (2002) has limited the use of predictive modeling for the evaluation of vapor intrusion, the Johnson and Ettinger model still provides the conceptual model most widely used today for the evaluation of vapor intrusion from VOCs dissolved in groundwater. This conceptual model is illustrated as Figure 1. The key features of this conceptual model include:

- *Equilibrium partitioning* of VOCs between bulk groundwater and the overlying SG
- *Diffusion* of VOCs from deep SG to shallow SG
- *Advection or diffusion* of VOCs from shallow SG to the base of the building slab, then through large cracks or the perimeter seal in the building slab into the building
- *Dilution* of VOCs in indoor air through exchange with ambient air.

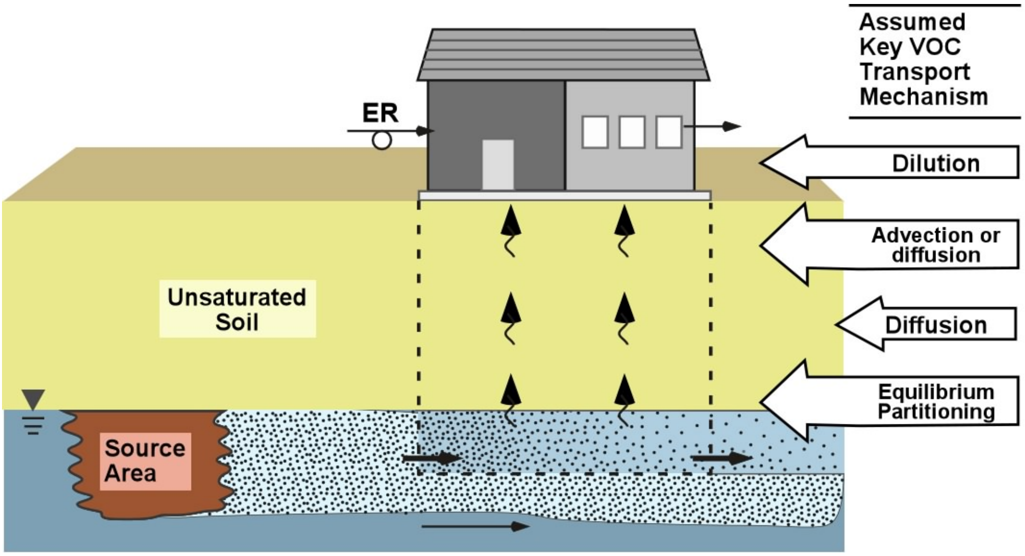

Figure 1. Current Conceptual Model for Vapor Intrusion. (Limitations of this conceptual model are discussed in Section 3.3)

Using this conceptual model, Johnson (2002) identified the critical parameters that are expected to control vapor intrusion at VOC-contaminated sites. Johnson predicted that the critical parameters would vary from site to site depending on the specific mechanism controlling the overall rate of vapor intrusion as follows:

Vapor intrusion limited by diffusion through soil

- Depth to subsurface VOC source
- Soil characteristics including soil permeability, soil saturation, and secondary porosity
- Building air exchange rate.

Vapor intrusion limited by diffusion through building foundation

- Foundation characteristics including thickness, area of foundation cracks, and crack permeability.

Vapor intrusion limited by advection through building foundation

- Ratio of SG intrusion rate to building ventilation rate.

Although Johnson (2002) identifies these critical parameters as those site characteristics most likely to determine the magnitude of vapor intrusion impacts at a VOC-contaminated site, he does not identify methods to determine which of the three potentially limiting processes is applicable at a specific site.

Although this conceptual model of vapor intrusion has been widely used to develop predictive vapor intrusion models (USEPA, 2000; Parker, 2003) and regulatory guidance, the conceptual model has not been thoroughly validated.

3.2 PROCESS DESCRIPTION

This demonstration was designed to collect a high density of data focused around individual test buildings in order to obtain a thorough understanding of vapor intrusion processes at the location. This high density data set was used to:

- Evaluate sample collection and analysis methods
- Evaluate and refine the current conceptual model of vapor intrusion, as described in Section 3 of this report
- Identify key environmental interfaces and site physical characteristics that impact the movement of VOCs along the vapor intrusion pathway
- Identify and validate a limited-scope site investigation to accurately evaluate vapor intrusion at corrective action sites.

In order to support these objectives, a sample collection program was designed as described below.

Sample Network: In order to provide a high density of data around an individual building, a network of sample points was installed at each demonstration building consisting of three clusters of four vertically-spaced groundwater wells; three clusters of four vertically spaced SG points; three subslab sample points; three indoor air sample points (with additional indoor air points for indoor tracer gas analyses); and three ambient air sample points. A conceptual illustration of the sample point network is provided as Figure 2.

Types of Samples Collected: For each sampling event, the samples were collected from each sample point and analyzed for VOC concentration. Additional analyses were conducted to understand the impact of site conditions on the distribution of VOCs around the demonstration buildings:

- *Geotechnical Data*. Soil samples collected during installation of the monitoring wells and SG points were analyzed for bulk density, fraction organic carbon, total porosity, water saturation, intrinsic permeability, and native hydraulic conductivity.
- *Oxygen and Carbon Dioxide*. During the initial sampling event at each site, subsurface samples were analyzed for oxygen and carbon dioxide. These analyses were not included in the subsequent sampling events based on the low variation in concentration observed between samples for these analytes.
- *Radon Analyses*. Subslab, indoor, and ambient air samples were analyzed for radon in order to evaluate the movement of SG through the building foundation.
- *Indoor Tracer*. Sulfur hexafluoride (SF_6) was released inside each demonstration building during each sample event, and measured indoor SF_6 concentrations were used to evaluate building air exchange rates. For some follow-up sampling events, SF_6 concentrations were measured in subslab samples to evaluate air flow from inside the building through the foundation.

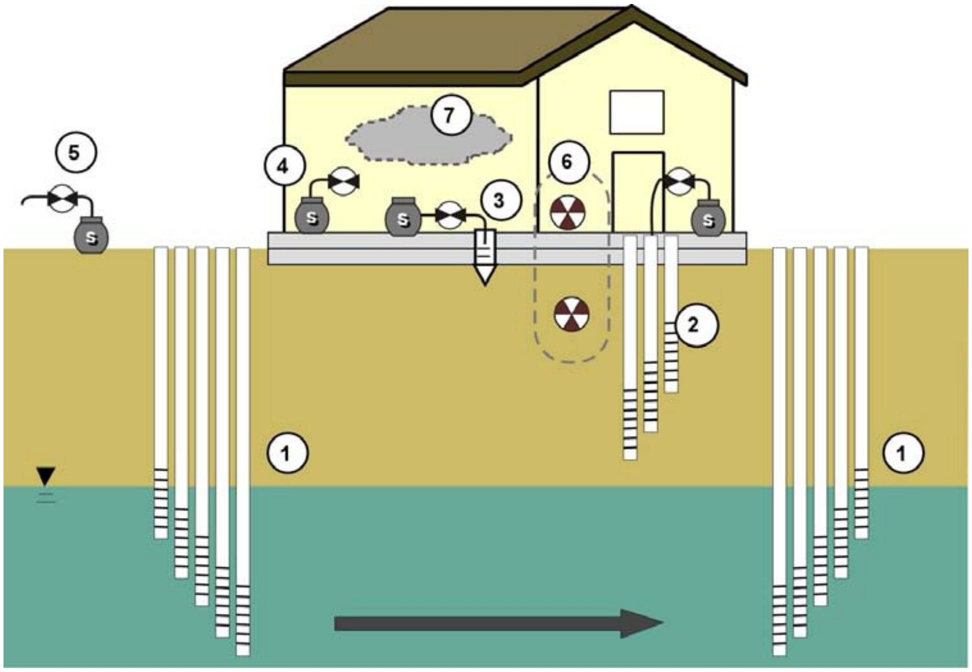

Figure 2. Conceptual Data Collection Plan for Detailed Evaluation Of The Vapor Intrusion Pathway. (1. Multilevel discrete depth samples upgradient, midgradient, and downgradient of the building used to characterize groundwater mass flux [three multilevel clusters]; 2. Multilevel SG sampling conducted below or adjacent to the building used to characterize SG concentration gradients and mass flux [three multilevel clusters]; 3. Subslab SG samples, combined with the other data, provide an understanding of transport from the groundwater source to indoor air [three sample points]; 4. Indoor air samples [three sample points] combined with 5. Ambient air samples [three sample points], and 6. Analysis of radon allows separation of indoor air sources and vapor intrusions sources; 7. Unique tracer gas released within the building allows for accurate measurement of building air exchange rate)

- *Leak Tracer*. For SG samples collected adjacent to the demonstration buildings, a leak tracer (pentane, 1,1-DFA, or SF_6) was used to evaluate the integrity of the sample points and sample collection lines.
- *Cross-Foundation Pressure Gradient*. During each sampling event, the cross-foundation pressure gradient was measured over a period of at least 24 hours.
- *Soil Permeability*. During the follow-up sample events, soil permeability was measured at selected SG points and unsaturated monitoring well locations by measuring the vacuum induced at various air flow rates.
- *Building Depressurization*. During the follow-up sampling at Hill Air Force Base (AFB) Residence #1, the impact of induced negative building pressure on indoor air quality was evaluated. For this evaluation, additional indoor and subslab samples were collected for VOC, radon, and SF_6 analyses.

In order to ensure that data were comparable between buildings and between sample events, the sample point design (see Section 4.4) was not varied between buildings. Sample collection (See Section 4.5) and analysis methods were also consistent from event to event; however, minor changes to the sampling program were implemented based on lessons learned during the early sampling events.

3.3 PREVIOUS TESTING OF THE TECHNOLOGY

The commonly used conceptual model of vapor intrusion described in Section 3.1 has been evaluated by a number of researchers, resulting in the identification of several areas of uncertainty and the need for further investigation. Key areas of uncertainty in the current groundwater-to-indoor-air vapor intrusion conceptual model are:

- **Johnson-Ettinger Model:** An evaluation of the Johnson-Ettinger Model based on a comparison between predicted and measured vapor intrusion impacts at 10 well characterized sites indicates a typical model error of 100x to 1,000x compared to measured indoor air impacts (Hers, Zapf-Gilje et al., 2003; McHugh, Connor et al., 2004b). These results indicate that the Johnson-Ettinger model has limited utility for the evaluation of vapor intrusion and suggests that the model may not account for key processes that control vapor intrusion impacts.
- **Consideration of the Water-SG Interface:** The current conceptual model assumes equilibrium partitioning of VOCs between the bulk groundwater plume and the overlying SG. In contrast, a number of studies focused on the groundwater-SG interface have demonstrated the importance of vertical diffusion in groundwater as the controlling process in the movement of VOCs from groundwater to SG (Barber, Davis et al., 1990; McCarthy and Johnson, 1993; McHugh, Connor et al., 2003). The incorrect and incomplete understanding of the mechanisms of VOC transfer from groundwater to the SG phase may contribute to overestimation of potential vapor intrusion impacts. Detailed measurements of VOC concentration gradients at the groundwater-SG interface are needed to better understand the importance of this transfer to overall vapor intrusion.
- **Site Characteristics:** Roggemans et al. (2001) looked at 28 sites with VOC contamination and classified them into four groups based on the vertical profile of VOC concentrations in the vadose zone. The researchers, however, were unable to identify the soil or other site characteristics that contributed to the differences in the observed concentration profiles. Measurement of soil characteristics such as grain size, porosity, and saturation, in conjunction with the measurement of VOC distribution, will contribute to a better understanding of the impact of soil characteristics on VOC distribution.
- **Evaluation of Indoor Air Background Conditions:** Background concentrations of VOCs in indoor air can vary greatly from building to building, depending on the presence and nature of site-specific indoor sources of these chemicals (paints, adhesives, cosmetics, gasoline, etc.). Consequently, the presence of VOCs in indoor air, even at levels in excess of average local or national background concentrations, is not necessarily indicative of actual vapor intrusion impacts. Conversely, in some cases, vapor intrusion effects may be masked by the magnitude and variability of background VOC concentrations. A thorough characterization of indoor VOC sources is needed to separate

indoor VOC sources from actual vapor intrusion impacts (McHugh, Connor et al., 2004a).

- **Reversible Advection Across Building Foundation:** The conceptual model of vapor intrusion assumes that VOCs move in one direction from the subsurface into the building by advection or diffusion (McHugh, DeBlanc et al., 2006). However, buildings often cycle between positive and negative pressure relative to the subsurface, resulting in reversing advective flow into and out of the building. This advective flow can result in the transport of VOCs from the building into the subslab, further complicating the evaluation of the vapor intrusion pathway.

In summary, the currently used vapor intrusion predictive and conceptual models are unable to account for the large variations in vapor intrusion observed within and between corrective action sites. Intensive characterization of a small number of VOC-contaminated sites provides an increased understanding of key vapor intrusion processes and serves as the basis to refine the current conceptual model of vapor intrusion.

3.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Vapor intrusion into an occupied building will always result in an inhalation exposure to site contaminants, potentially resulting in unacceptable health risks or other conditions that require a response action. Incorrectly concluding that a vapor intrusion impact has not occurred can result in a failure to mitigate the associated health risks and may result in health claims or litigation if the problem is identified in the future. Incorrectly concluding that a vapor intrusion impact has occurred can result in unnecessary mitigation costs and may also result in litigation or third-party claims. The advantages and disadvantages of vapor intrusion field investigation and presumptive mitigation are discussed below.

Vapor Intrusion Field Investigation. An effective vapor intrusion field investigation will often yield a definitive determination of the presence or absence of a vapor intrusion impact. At sites where the investigation demonstrates the absence of a vapor intrusion impact, no further evaluation of vapor intrusion will be required. At these sites, the available resources can be focused on the evaluation and remediation of other site impacts. At sites where the investigation demonstrates a vapor intrusion impact, this impact can be mitigated through interim response actions and addressed as part of the comprehensive site remediation.

Presumptive Mitigation. The vapor intrusion pathway is unusual compared to other exposure pathways typically evaluated at corrective action sites because the cost of implementing an exposure prevention remedy is often small compared to the cost of site investigation. The installation of a subslab depressurization system is relatively inexpensive ($4,000 to $8,000 per building for a typical single family residence). As a result, the USEPA vapor intrusion guidance recommends installation of subslab depressurization systems as a cost-effective alternative to extensive site investigation at sites where vapor intrusion may be causing indoor air impacts. Based on our current limited understanding of the site-specific factors contributing to vapor intrusion impacts, installation of a subslab depressurization system may frequently be more cost effective than conducting a site investigation to determine whether vapor intrusion is, in fact, a problem. However, this approach has a number of limitations:

- **Perception Problems:** The installation of a depressurization 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.
- **Evaluation of Effectiveness:** Because of indoor air background VOCs, it can be difficult to verify that the depressurization system is operating effectively to prevent vapor intrusion.
- **System-Wide Costs:** Although the cost of a single depressurization system is low, the total cost for multiple buildings over a portfolio of corrective action sites would be quite high.

Due to the high costs associated with installing depressurization systems at a large number of corrective action sites or conducting field investigations of vapor intrusion at a large number of corrective action sites, a better understanding of vapor intrusion processes that supports more effective site investigation procedures have the potential to significantly reduce both site investigation and remediation costs.

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4.0 DEMONSTRATION DESIGN

4.1 PERFORMANCE OBJECTIVES

The primary objective of this demonstration study is to identify and validate the limited site investigation scope that provides the most accurate and reliable evaluation of vapor intrusion at corrective action sites. This objective is met by:

- Collecting a high density of data related to vapor intrusion at the test sites
- Analyzing this data to obtain a thorough understanding of vapor intrusion processes at the test sites
- Utilizing the results to develop a reliable and cost-effective approach for investigation of vapor intrusion at other sites.

Specific performance objectives cover collection of data representative of site conditions and evaluation of the data to identify improved vapor intrusion investigation methodology. The objectives are summarized in Table 3.

Table 3. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	1. Collection of data representative of site conditions	Precision, accuracy, completeness, representativeness, and comparability	Objective attained (See Section 5.1 and 5.2)
Quantitative	2. Vapor intrusion impact at demonstration site	Indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources	Objective attained (See Section 5.3)
Qualitative	3. Reliable vapor intrusion investigation approach	Accuracy of vapor intrusion determination as characterized by false positive and false negative rates. Identify limited scope investigation approach with higher accuracy than current approaches such as USEPA (2002)	Objective attained (See Section 5.3)

Details concerning the site investigation and data analysis methods used to achieve these performance objectives are provided in Section 5.

4.2 SELECTING TEST SITES

For this demonstration, sites were selected to maximize the potential to improve our understanding of VOC migration from dissolved groundwater plumes to overlying buildings. The following criteria were used to identify test sites likely to yield interpretable data: 1) Presence of VOC impacts to groundwater at concentrations above 10 μg/L, 2) Depth to groundwater of 5 to 20 ft below ground surface (bgs), 3) Sufficient access to demonstration buildings for sample collection, and 4) Presence of existing information concerning site characteristics.

4.3 TEST SITE DESCRIPTION

Altus AFB, Altus, Oklahoma: The first location selected for the field vapor intrusion investigation was in and around Building 418 on Altus AFB, located near the southern boundary of the facility. A map of the facility, including the location of Building 418, is presented in Appendix C of the project Final Report. The groundwater plume underlying the test building has been extensively characterized as part of the remedial field investigation (RFI) process underway at Altus.

The test building is a single-story slab-on-grade office building approximately 150 ft long by 50 ft wide. The building is used primarily for classroom instruction. Based on the small size and nonindustrial use, the building is representative of large houses, small apartment buildings, and small office buildings. The test building is underlain by a shallow dissolved chlorinated solvent groundwater plume containing elevated concentrations of tetrachloroethene (PCE), trichloroethene (TCE), and 1,2-dichloroethene (1,2-DCE). This plume has been designated the SS-17 plume.

The local subsurface geology consists of clay, sandy clay, residual soils resulting from the weathering of shale, and alluvium resulting from the erosion and deposition of surface materials (which includes fill associated with construction activities). The fill, clay, disturbed residual soils, and alluvium are difficult to separate and are collectively referred to as the sediment/overburden. This sediment/overburden appears to cover the entire site. The transition from sediment/overburden to the more competent shale is not a readily defined horizon; however, the sediment/overburden is generally considered to extend 12 to 20 ft bgs in the vicinity of Building 418.

Hill AFB, Ogden, Utah: The second vapor intrusion field investigation was conducted at Operable Unit 5 (OU-5), a dissolved TCE plume originating on Hill AFB and extending off-base to the west. The investigation focused on two residential houses overlying this TCE plume. A map of the area showing the location of the two buildings is presented in Appendix C of the project Final Report. The first residence (Residence 1) is located near the corner of 690 West and 2550 North in the community of Clinton. TCE concentrations in shallow groundwater in the vicinity of this residence are between 10 and 100 μg/L. The second residence (Residence 2) is located near the corner of 175 West and 2125 North in the community of Sunset. TCE concentrations in shallow groundwater in the vicinity of the test building are around 100 μg/L.

The shallow groundwater-bearing unit underlying OU-5 is characterized by fine grain sand and silt, with the silt content increasing with depth. The upper portion of the unit is characterized by fine to very-fine-grained yellowish-brown sand. The silt content generally increases with depth, grading into a clay at 20 to 30 ft below ground that serves as a confining layer isolating shallow groundwater from deeper water-bearing units. This clay unit is made up of 85 to 95% silt and clay particles and is a dark grayish-brown clayey silt of low permeability. COC impacts have been observed in the shallow groundwater-bearing unit but not in the underlying confining layer or deeper water-bearing units.

4.4 PHYSICAL SETUP AND OPERATION

For this site investigation demonstration, the installation program consisted of the installation of subsurface sample points. Sample points were installed at Altus AFB in March 2005 and at Hill AFB in August 2005. A total of 27 subsurface sampling points were installed around and under each of the three demonstration buildings (see Figure 2).

Groundwater Monitoring Well Points: Monitoring wells for groundwater and well headspace sampling were installed using traditional direct-push techniques. Three monitoring well clusters were installed around each building with each cluster consisting of four wells with vertically spaced screens. Example construction specifications are shown in Figure 3.

SG Points: Two vertical clusters of SG points were installed outside, adjacent to each demonstration building and one vertical cluster was installed through the building foundation. The SG points installed outside were installed in the same manner as the monitoring wells using direct-push techniques to depths of 1, 2, 3, and 4 ft bgs. Example construction specifications are shown in Figure 3. Indoor SG points were installed at the midgradient cluster to depths of 1, 2, 3, and 4 ft bgs. Example construction specifications are shown in Figure 3.

Subslab Sample Points: Sample points for the collection of subslab gasses were installed by drilling a 1/2-inch hole through the building slab and into the underlying soil or fill material to a depth of 3 to 4 inches below the base of the foundation. Example construction specifications are shown in Figure 3.

Initial sampling events were conducted the week after installation of the sampling points at each demonstration site (Altus AFB in March 2005 and Hill AFB in September 2005). In order to characterize temporal variability, three follow-up sampling events were conducted at Altus AFB (March 2005, July 2006, and December 2006) and one follow-up sampling event was conducted at Hill AFB (March 2006).

4.5 SAMPLING/MONITORING PROCEDURES

The types of samples collected are summarized in Section 3.2. At least two sampling events were conducted at each demonstration building. The sample events are described below and summarized in Table 4.

- *Sample Point Purge Study*. Prior to the first full sample event at each location, a purge study was conducted on the SG sample points to evaluate the impact of sample point purge volume on measured VOC concentration. Based on the results of these studies, a purge volume of three sample line volumes was used for collection of subsequent samples.

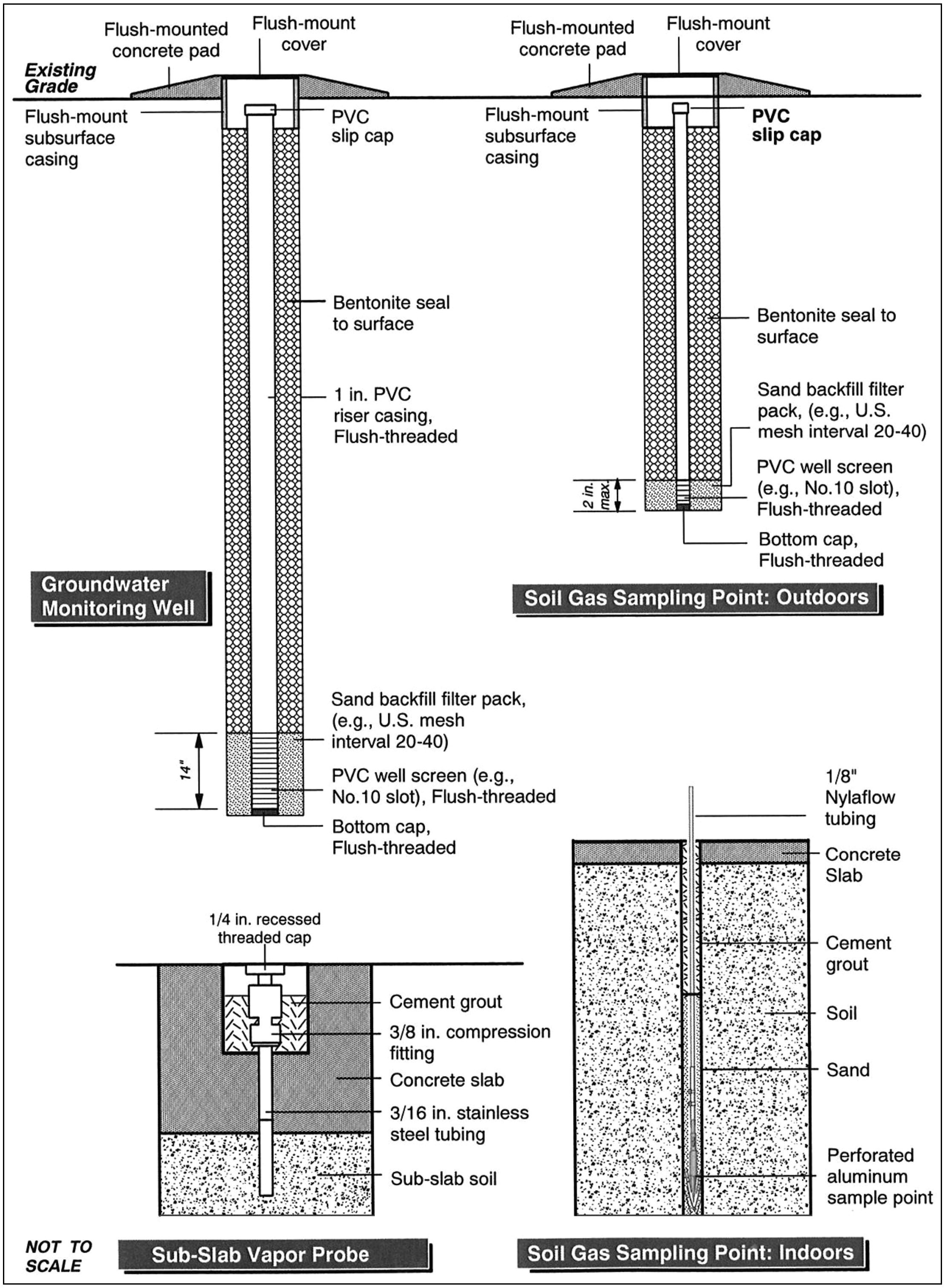

Figure 3. Typical Construction Specifications for Sample Points.

Table 4. Summary of Sample Collection by Sampling Event.

Sample Event	Sample Type							
	VOCs	Soil Geotech.	O2 / CO2	Radon	Indoor Tracer	Leak Tracer	Soil Perm.	Building Depress.
Altus AFB Building #418								
Soil gas point purge study	X					X		
Initial sampling event	X	X	X	X	X			
Short-term follow-up	X		X	X				
Longer term follow-up #1	X			X	X	X	X	
Longer term follow-up #2	X			X	X	X	X	
Hill AFB Residence #1								
Soil gas point purge study	X					X		
Initial sampling event	X	X	X	X	X			
Longer term follow-up	X			X	X	X	X	
Building depressurization	X			X	X			X
Hill AFB Residence #2								
Soil gas point purge study	X					X		
Initial sampling event	X	X	X	X	X			
Longer term follow-up	X			X	X	X	X	

- *Initial Sampling Event*. At each location, an initial sampling event was conducted approximately one week after installation of the subsurface sampling points. For the initial sampling event, samples were collected and analyzed for VOCs, oxygen and carbon dioxide, geotechnical analyses, radon, indoor tracer, and leak tracer.
- *Evaluation of Short-Term Variability (Days)*. At the Altus AFB demonstration building, samples were collected two days after the initial sampling event. The results of these analyses were used to evaluate temporal variability on the time scale of days. For this sampling event, samples were collected and analyzed for VOCs and radon.
- *Evaluation of Longer Term Variability (Months)*. At the Altus AFB demonstration building, follow-up sampling events were conducted 16 months and 22 months after the initial sampling event. At the two Hill AFB demonstration buildings, follow-up sampling was conducted 6 months after the initial sampling event. For these sampling events, samples were collected and analyzed for VOCs, radon, indoor tracer, and leak tracer. In addition, soil permeability was measured at selected points.
- *Building Depressurization*. The building depressurization study was conducted at Hill AFB Residence #1 immediately after the follow-up sampling event.

The typical sample collection and analysis program is summarized in Table 5. Detailed sample collection procedures are provided in the project Demonstration Plan and the project Final Report. Detailed data quality objectives (DQO) are specified in the Quality Assurance Project Plan (QAPP) included as Appendix B of the project Final Report.

Table 5. Summary of Sample Collection and Analysis Program for a Typical Sampling Event.

Matrix	Number of Samples	Sample Volume	Container	Analytical Method	Holding Time	Lab	Sample Collection Timing
Groundwater	Up to 24	3 x 40 mL	Volatile organic analysis (VOA) vial w/ hydrochloric acid (HCL)	8260B (VOCs)	14 days	STL Houston	1 event/ building
Well headspace	6	400 mL*	Summa*	TO-15* (VOCs)/SF_6	14 days	Columbia Analytical*	1 event/ building
Soil gas	24	400 mL*	Summa*	TO-15* (VOCs)/SF_6	14 days	Columbia Analytical*	1 event/ building
Subslab gas	3	400 mL*	Summa*	TO-15* (VOCs)/SF_6	14 days	Columbia Analytical*	1 event/ building
Indoor air	3	6 L*	Summa*	TO-15 SIM* (VOCs)	14 days	Columbia Analytical*	1 event/ building
Indoor air tracer	6	250 mL	Tedlar bag	SF_6	3 days	Columbia Analytical*	1 event/ building
Ambient	3	6 L*	Summa*	TO-15 SIM* (VOCs)	14 days	Columbia Analytical*	1 event/ building
Ambient radon	2	100 mL	Evacuated canister	Mathieu, 1998 (Radon)	3 days	University of Southern California	1 event/ building
Indoor air radon	3	100 mL	Evacuated canister	Mathieu et al., 1998 (Radon)	3 days	University of Southern California	1 event/ building
Subslab radon	3	100 mL	Evacuated canister	Mathieu et al., 1998 (Radon)	3 days	University of Southern California	1 event/ building

Note: (1) * = For the initial sampling event at each demonstration building, some VOC analyses were conducted by H&P Mobile Geochemistry using an on-site mobile laboratory. For these analyses, 50-mL samples were collected using 60-mL gas tight syringes. (2) Number of samples does not include additional samples collected for quality assurance/quality control (QA/QC). (3) Geotechnical samples and vadose zone permeability testing not included.

4.6 ANALYTICAL PROCEDURES

Traditional methods for the analysis of soil and groundwater were implemented in this investigation. All of the laboratory methods selected represent standard methods developed by the USEPA, American Society for Testing and Materials (ASTM), or American Petroleum Institute (API). These methods have been thoroughly validated and widely applied at corrective action sites, providing a high level of assurance in their ability to provide accurate results.

Groundwater samples were analyzed by EPA method 8260 for quantification of specific VOCs.

During the initial investigation at each site, air and SG samples were screened by USEPA method 8021 (direct gas chromatography) using an on-site mobile laboratory and further analyzed by USEPA method 8260B. This two-tiered analysis procedure allowed for efficient utilization of the on-site mobile laboratory while still providing accurate quantification of both high concentration and low concentration samples. During the subsequent sampling events at both sites, indoor and ambient samples were analyzed by the TO-15 selective ion monitoring (SIM) method (low level) for a select list of compounds; all other vapor samples were analyzed by the standard TO-15 method. Gas samples requiring SF_6 analysis were analyzed using a modified NIOSH 6602 method, which utilizes a gas chromatograph with an electron capture detector.

Soil samples were analyzed for geotechnical parameters by ASTM and API methods (ASTM D2216 and API 40). Geotechnical parameters selected for analysis include bulk density, fraction organic carbon, porosity, permeability to water, and hydraulic conductivity.

Radon gas samples were collected in vacuum cells or Tedlar bags for radon analysis, and were analyzed as described in McHugh et al. (2008) at the University of Southern California. Additional radon samples collected by means of pre-weighed activated carbon canisters were analyzed using USEPA Method #402-R-93-004 079 and had a method detection limit of 0.4 pCi/L.

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5.0 PERFORMANCE ASSESSMENT

5.1 PERFORMANCE DATA

The sample collection and analysis program yielded a large data set of sufficient quality to meet the DQOs and evaluate the technology performance. The data quality is summarized in Table 6. A DQOs and a detailed evaluation of the project data are provided in the project Final Report.

Table 6. Summary of Data Evaluation Results.

Data Quality Objective	Results Of Data Quality Evaluation			
	Meets Data Objectives	Other Useable Data	Rejected Data	Comments
Custody, hold, temp	99%	1%	0%	
Sampling, instruments	99%	1%	0%	
Accuracy assessment	82%	13%	5%	Rejected TO-15 data and elevated detection limits.
Precision assessment	98%	2%	0.4%	
Completeness assessment	100%	0%	0%	

Note: Percentages based on total number of samples collected (675) including all QA/QC and mobile laboratory data, exclusive of purge study data.

5.2 PERFORMANCE CRITERIA

The primary objective of this demonstration study was to identify and validate the limited set of site investigation samples that provides the most accurate and reliable evaluation of vapor intrusion at corrective action sites. This objective is met by:

- Collecting a high density of data related to vapor intrusion at the test site
- Analyzing this data to obtain a thorough understanding of vapor intrusion processes at the test site
- Utilizing the results to develop a reliable and cost-effective approach for investigation of vapor intrusion at other sites.

The specific performance criteria utilized in this process are provided in Table 7. The primary performance criteria reflect the project performance objectives while the secondary performance objectives reflect the intermediate data evaluation results that support the project objectives.

Table 7. Expected Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Performance Criteria for Data Quality Assurance (Quantitative)			
Precision	+/- 30% relative percent difference (RPD)	One duplicate per 20 samples for all VOC analyses (water and air/gas)	RPD goal met in 82% of duplicate pairs
Accuracy	Field blanks below practical quantitation limits (PQL) Laboratory accuracy as defined in QAPP	All VOC analyses (water and air/gas)	Goal achieved in 98% of field blanks and laboratory QA/QC samples
Completeness	> 90% valid field samples >95% valid laboratory results	All VOC analyses (water and air/gas)	Achieved
Performance Criteria for Data Quality Assurance (Qualitative)			
Representativeness	Use of field sampling procedures, laboratory analytical procedures, sample holding times, etc. defined in QAPP	All field samples	Goal achieved for 99% of samples
Comparability	Use of standard and consistent sampling and analysis procedures for all samples, as defined in QAPP	All field samples	Goal achieved for 99% of samples
Performance Criteria for Technology Demonstration (Qualitative and Quantitative)			
Vapor intrusion impact	Presence or absence of vapor intrusion impact at test site. Vapor intrusion impact defined as indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources.	Detection of VOCs in indoor air at concentrations exceeding USEPA (2002) indoor air screening limits. If limits exceeded, evaluation of subslab and indoor air data to separate vapor intrusion from background indoor air sources.	Evaluation of indoor, ambient, and subslab VOC and radon concentrations indicated an absence of vapor intrusion impacts above applicable regulatory limits in all three demonstration buildings during each sampling event.
Movement of VOCs across key interfaces	Calculation of mass flux across key vapor intrusion pathway interfaces	Consistent or decreasing mass flux along the vapor intrusion pathway	Calculated mass flux values had high uncertainty and did not show a consistently decreasing mass flux along the vapor intrusion pathway.

Table 7. Expected Performance and Performance Confirmation Methods. (continued)

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Spatial and temporal variability in VOC concentration	Calculation of spatial and temporal variability in chemical concentration for each environmental medium investigated	Statistical measures of variability	High spatial and longer term (months) temporal variability in subsurface VOC concentrations compared to above-ground VOC concentrations indicate that a larger number of samples are required to characterize subsurface media. Short-term temporal variability (days) does not appear to be a major source of uncertainty in vapor intrusion evaluations.
Attenuation factors	Calculation of attenuation factors describing the attenuation of chemicals from various environmental media to indoor air	Statistical measures of variability	Calculated attenuation factors had moderate to high uncertainty but were consistently below USEPA default values for pathway screening. Measured subslab to indoor air attenuation factors ranged from 3.8 x 10-4 to 7.6 x 10-3. Measured groundwater to indoor air attenuation factors ranged from 2.9 x 10-6 to 3.6 x 10-4.
Site physical characteristics	Measurement of site soil characteristics and other physical characteristics of the site	Correlation of site characteristics to VOC distributions and fluxes	Data set did not show expected correlation between lower soil permeability and higher VOC attenuation.
Reliable vapor intrusion investigation approach	Identification a limited site investigation program that will provide a reliable indication of vapor intrusion impacts	Statistical comparison of accuracy of vapor intrusion impact predicted by limited subset of site data compared to full set of data obtained for the site	We have developed a recommended approach for the reliable investigation of vapor intrusion.

5.3 DATA ASSESSMENT

Project data support the following findings:

Vapor Intrusion Impact: A vapor intrusion impact, defined as an exceedance of applicable indoor air VOC concentration screening values attributable to vapor intrusion, was not observed in any of the demonstration buildings. However, a statistically significant increase in indoor VOC concentration relative to ambient concentrations was observed during some sample events. The analysis of VOC and radon concentrations in ambient air, indoor air, and subslab gas samples provided a data set that could be used to identify the most likely source of VOCs detected in indoor air. The data evaluation indicated some migration of TCE and/or PCE from the subsurface to indoor air at the demonstration buildings during some sample events; however, in all cases, the estimated VOC concentration in indoor air attributable to vapor intrusion was below the applicable screening level for the site.

Use of Radon as a Tracer for SG Movement into Buildings: Based on the difference between indoor and ambient radon concentrations and the absence of indoor sources of radon, radon was determined to be a sensitive tracer for the movement of SG through the building foundation. The measured radon attenuation factors have been used to calculate the concentration of VOCs in indoor air attributable to vapor intrusion and to evaluate the possible contribution of indoor VOC sources to measured indoor VOC concentrations. Radon is a useful tracer for the movement of SG because radon is emitted from all soils and is present in all SG. However, because VOCs in SG originate from specific contaminant sources (e.g., contaminated groundwater) while radon in SG originates from all soils, the distribution of radon and VOCs may be different within subsurface gas below a building. In other words, VOC concentrations and radon concentration in SG do not perfectly co-vary. As a result, while radon is a good tracer for the movement of SG into a building, it is not a perfect tracer for the movement of subsurface VOCs into a building. Radon data is likely to be most useful for the evaluation of vapor intrusion when radon and VOC concentrations are measured at multiple sub-slab sample locations allowing for an evaluation of the differences in subsurface distribution of these chemicals.

Movement of VOCs Across Key Interfaces: Measured VOC concentrations in groundwater, SG, and indoor air along with measurement of site physical parameters (e.g., groundwater flow velocity, soil permeability, etc.) were used to estimate VOC mass flux within and across environmental media. These mass flux estimates were then used to evaluate the movement of VOCs across key interfaces along the vapor intrusion pathway. Mass flux through shallow groundwater was consistently higher than mass flux through SG or through the building foundation. This indicates that only a small fraction of the VOC mass diffused from groundwater to SG during the migration of groundwater under the demonstration building. In contrast, no consistent relationship was observed between estimated mass flux through SG and through the building foundation. The large uncertainty in mass flux estimates may limit their utility for evaluation of vapor intrusion.

Spatial and Temporal Variability in VOC Concentration: Demonstration results were analyzed to determine the most important sources of variability in VOC concentrations during vapor intrusion investigations. RPD was used to describe variability between paired measurements, and coefficient of variation (CV) was used to describe variability in data sets of three or more measurements. Analytical variability was very low with an average RPD between laboratory duplicate measurements of 2.5% and surrogate recoveries typically between 98% and 102%. Field duplicate variability was higher but acceptable, with 78% of field duplicate VOC measurements achieving the DQO of an RPD<30%. Considering all field duplicates (i.e., VOC, radon and SF_6 measurements), 82% of project samples met the DQO. RPD ranged from 0% to 182% (Note: 182% RPD = 22 x difference), with an average RPD of 25%. Short-term temporal variability (i.e., time scale of days) was only slightly higher than field duplicate variability with 65% of duplicate VOC measurements showing an RPD<30%. These results indicate the variability on the time scale of days was largely influenced by sample collection and/or very small-scale field variability.

Spatial variability in VOC concentration was evaluated through the CV in VOC concentrations between samples from three spatially separated sample points. Spatial variability was much higher in subsurface gas samples (i.e., average CV = 0.92 to 0.96 in subslab, SG, and well headspace samples) compared to indoor (average CV = 0.26) and ambient air samples (average CV = 0.55). Based on this finding, an efficient vapor intrusion investigation program that includes samples from both media should include a larger number of subsurface gas samples than above-ground air samples. Longer term temporal variability (i.e., time scale of months) in subsurface gas samples was similar to the spatial variability (i.e., average CV = 0.80 to 1.02 in subslab, SG, and well headspace samples). This finding suggests that subsurface gas sampling should be balanced between spatially separated sample points and temporally separated sample events.

Attenuation Factors: As a result of the high spatial variability in subsurface VOC concentration, there was significant uncertainty in the calculated subsurface to indoor air attenuation factors. The standard deviation for the calculated attenuation factors was typically similar to or greater than the attenuation factors themselves. Despite this uncertainty, the calculated attenuation factors were consistently less than the USEPA default values, indicating that the USEPA default values were conservative and protective for the three demonstration buildings evaluated. Measured subslab to indoor air attenuation factors ranged from 3.8×10^{-4} to 7.6×10^{-3} compared to the current USEPA default value of 1.0×10^{-1} and the proposed value of 5.0×10^{-2}. Measured groundwater to indoor air attenuation factors ranged from 2.9×10^{-6} to 3.6×10^{-4} compared to the current USEPA default value of 1.0×10^{-3} (the USEPA has not proposed a change to this default value). Typically, attenuation factors are calculated based on a single subsurface and a single indoor air measurement. For this project, each attenuation factor was calculated based on a minimum of three subsurface and three indoor air measurements. The high uncertainty associated with these relatively data rich attenuation factors indicates that typical attenuation factors are extremely uncertain and may have limited utility for evaluation of the vapor intrusion pathway.

Site Physical Characteristics: The demonstration yielded a limited data set for the evaluation of site physical characteristics, supporting only a limited evaluation of the impact of site characteristics on vapor intrusion. However, the available data do not support the hypothesis that lower permeability vadose zone soils decrease the potential for vertical migration of VOCs from groundwater through the unsaturated soil column, decreasing the potential for vapor intrusion impacts.

Recommendations for Investigation of Vapor Intrusion: The results of the demonstration have been used to develop a recommended sample collection program for the evaluation of vapor intrusion in individual buildings, summarized in Table 8.

Table 8. Recommended 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	6 L Summa	1	Upwind
	Radon[2]	Grab	0.5 L Tedlar	1	
Indoor air	VOCs by TO-15[1]	24 hr	6 L Summa	1 - 2[3]	Lowest floor
	Radon[2]	Grab	0.5 L Tedlar	1 - 2[3]	
Subslab gas	VOCs by TO-15	Grab	0.4 L or 1 L 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 as described in McHugh et al. (2008). Analysis of radon in gas samples is not currently available from commercial environmental laboratories. However, Dr. Hammond will conduct the analysis for environmental consultants and other parties.

[3] Recommended number of samples for a typical residence with a 1,000 – 2,000 ft^2 foundation. Additional samples may be appropriate for larger structures.

The results of the investigation program should be used to evaluate vapor intrusion 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 concentrations 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 TCE attenuation factor of 0.001 would suggest a likely indoor source of PCE.
- *Evidence of vapor intrusion*. The following factors together indicate that vapor intrusion is likely the primary source of observed indoor air impacts: 1) Indoor VOC concentrations greater than ambient VOC concentrations, 2) Below foundation to indoor

air attenuation factors <0.01, and 3) Below foundation to indoor air attenuation factors similar for all VOCs and for radon.

Typical costs for the recommended investigation approach are provided in Section 6.2 below.

5.4 TECHNOLOGY COMPARISON

Currently available regulatory guidance does not provide clear and consistent recommendations for the field evaluation of vapor intrusion at individual buildings. As a result, the current approaches to the investigation of vapor intrusion vary widely between sites. When comparing investigation results between sites, it is difficult to separate the effects of site characteristics from the effects of differing investigation methods. The application of a consistent field investigation program, such as that recommended here, across buildings and sites will yield comparable data sets that provide an improved understanding of the site-specific factors contributing to the presence or absence of vapor intrusion impacts at individual buildings.

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6.0 COST ASSESSMENT

6.1 COST REPORTING

As a site characterization technology, the key cost components of the demonstration were 1) sample point installation, 2) sample collection and analysis, and 3) data analysis and reporting. Costs for each field event are presented in Tables 9 and 10. Representative unit costs are presented in Section 6.2.

Table 9. Contractor and Materials Costs.

Cost Category	Sub Category	Sample Event				
		Altus 1 Mar 05	**Hill 1 Sept 05**	**Hill 2 Mar 06**	**Altus 2 Jul 06**	**Altus 3 Dec 06**
Project planning and preparation		N/A	N/A	N/A	N/A	N/A
Installation of monitoring points adjacent to building by direct-push technology (12 wells and 8 soil gas [SG] points in 3 clusters)	Contractor costs	$8,700	$8,700	N/A	N/A	N/A
	Materials costs	$920	$5,100	N/A	N/A	N/A
Installation of monitoring points through foundation (3 subslab pts and 4 deeper soil gas pts)	Contractor costs	N/A	N/A	N/A	N/A	N/A
	Materials costs	$100	$100	N/A	N/A	N/A
Sample collection	Materials, consumables, equipment rental, shipping	$4,100	$5,700	$1,400	$800	$500
Sample analysis	Geotechnical samples (9 samples/blding)	$2,700 (9 samples)	$4,800 (18 samples)	N/A	N/A	N/A
	Groundwater samples	$1,700 (20 samples)	$2,400 (17 samples)	$2,900 (24 samples)	$1,400 (10 samples)	$1,400 (10 samples)
	Air/gas sample (mobile lab)	$20,500 (101 samples)	$20,500 (113 samples)	N/A	N/A	N/A
	Air/gas sample (off-site lab)	N/A	$5,800 (14 samples)	$22,000 (69 samples)	$12,100 (30 samples)	$9,900 (35 samples)
	Radon	$500 (11 samples)	$700 (11 samples)	$2,900 (32 samples)	$800 (20 samples)	$1,000 (18 samples)
Data evaluation and reporting	Consumables	$100	$100	$100	$100	$100

Note: See Tables 4 and 5 for additional details on the samples collected during each event.

Table 10. Consultant Labor Requirements (Hours)**.**

Cost Category	Sub Category	Sample Event				
		Altus 1 Mar 05	**Hill 1 Sept 05**	**Hill 2 Mar 06**	**Altus 2 Jul 06**	**Altus 3 Dec 06**
Project planning and preparation	Scientist/ engineer	170	200	120	100	50
	Technician	20	30	10	40	10
Installation of monitoring points adjacent to building by direct-push technology (12 wells and 8 soil gas points in 3 clusters)	Scientist/ engineer	50	40	N/A	N/A	N/A
	Technician	40	20	N/A	N/A	N/A
Installation of monitoring points through foundation (3 Subslab pts and 4 deeper soil gas pts)	Scientist/ engineer	10	20	N/A	N/A	N/A
	Technician	20	40	N/A	N/A	N/A
Sample collection	Scientist/ engineer	110	100	80	60	60
	Technician	0	0	0	0	0
Sample analysis	Scientist/ engineer	N/A	N/A	N/A	N/A	N/A
	Technician	N/A	N/A	N/A	N/A	N/A
Data evaluation and reporting	Scientist/ engineer	400	230	120	110	60
	Technician	130	80	40	30	10

Note: Labor costs can be estimated by multiplying labor hours by the expected hourly labor rate. Scientist/engineer rates are commonly $100 to $200/hr. Technician rates are commonly $30 to $60/hr.

6.2 COST ANALYSIS

Representative unit costs for each component of the vapor intrusion investigation program are provided in Table 11. Typical costs for testing a single family residence for a vapor intrusion impact are provided in Table 12.

Table 11. Representative Unit Costs for Vapor Intrusion Investigation.

Cost Category	Sub Category	Representative Unit	Representative Unit Cost
Installation of monitoring points adjacent to building by direct push technology	Monitoring well (1-in diameter, 10-ft depth w/ 2-ft screen)	Monitoring well	$415
	Soil gas point (1/2-in diameter, 5-ft depth w/ 2-in screen)	Soil gas point	$415
Installation of monitoring points through foundation	Subslab point (3/16-in diameter penetration through foundation w/fittings installed for sample collection)	Subslab point	$133
	Soil gas point (4-ft depth, 1-in sample point connected to surface by 1/8-in tubing)	Soil gas point	$127
Sample analysis	Geotechnical samples	Soil core	$315
	Groundwater samples (VOCs by Method 8260)	Water sample	$100
	Air/gas sample (by Method 8260 in Mobile lab)	Air/gas sample	$350
	Air/gas sample (by Method TO-15 at off-site lab)	Air/gas sample	$310
	Air/gas sample (by Method TO-15 at off-site lab)	Air/gas sample	$340
	Radon (gas sample at off-site lab)	Air/gas sample	$100
	Radon (by carbon canister, indoor and ambient air only)	Air sample	$25
	SF_6 (by NIOSH Method 6602)	Air sample	$95

Note: Representative costs include all materials and labor costs for sample point installation and laboratory analysis of samples. Representative costs do not include labor costs for project planning, consultant oversight, sample collection, data analysis, or reporting.

Table 12. Typical Costs for Testing 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 Subslab - 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	**$5,710**
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. These costs assume testing of a single-family residence as part of a larger environmental investigation at a facility. Testing of a single-family residence in the absence of other related project work would entail higher project planning and reporting costs.

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7.0 IMPLEMENTATION ISSUES

7.1 COST OBSERVATIONS

As a site characterization technology, the key cost components of the demonstration were 1) sample point installation, 2) sample collection and analysis, and 3) data analysis and reporting. These costs are relatively easy to estimate and do not vary greatly between sites, as site-specific and other factors are not expected to significantly impact costs. In addition, costs are not expected to vary greatly with project scale.

7.2 PERFORMANCE OBSERVATIONS

All performance criteria for data quality and technology demonstration were achieved (see Table 7). Spatial and temporal variability in VOC concentrations is expected to have the greatest impact on technology performance. High spatial and long-term temporal variability in SG VOC concentration resulted in very high uncertainty associated with mass flux evaluation of the vapor intrusion pathway. This high variability also resulted in a large number of sample locations and sample events required to accurately characterize the VOC distribution in SG. High variability was also found in the calculation of subsurface to indoor air attenuation factors, further reinforcing the need to collect multiple samples to adequately characterize sites.

7.3 SCALE-UP

No scale-up issues are expected for this site characterization technology.

7.4 OTHER SIGNIFICANT OBSERVATIONS

Summa canisters are the most commonly used containers for the collection of SG 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. Use of individually certified clean Summa canisters is recommended as the most reliable way to ensure an absence of carry-over contamination when Summa canisters are used for VOC analysis of SG or air. 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.

7.5 LESSONS LEARNED

When collecting SG samples, use of a leak tracer is important to ensure that the collected sample is not impacted by significant leakage of ambient air. However, some leak tracer compounds, such as isopropyl alcohol, can cause elevated detection limits for target compounds if present in the sample at elevated concentrations. This analytical interference may occur at concentrations not indicative of a significant sample leak. As a result, the presence of leak tracer compound in SG samples may result in elevated detection limits for target analytes, invalidating samples that otherwise would be considered to have acceptable leakage rates. To avoid this problem, use a gas-phase leak tracer such as helium or SF_6. Confirm with the analytical laboratory that the tracer compound will not interfere with the analysis of target compounds.

7.6 END-USER ISSUES

The results of this demonstration have been used to develop a recommended approach for the cost effective, building-specific, evaluation of vapor intrusion impacts at corrective action sites (See Section 4.6 of the Final Report). Although the understanding of vapor intrusion processes is still evolving, the investigation approach presented in Section 4.6 has been developed to provide a reliable and cost effective determination of the presence or absence of vapor intrusion impacts at buildings overlying VOCs in groundwater or soil. The recommended approach includes a limited-scope initial screening to eliminate buildings with no elevated concentrations of VOCs, and a more comprehensive follow-up evaluation program to reliably determine the source of any detected VOCs. The stepwise screening and field investigation approach will benefit facility managers by providing investigation results that support a defensible evaluation of vapor intrusion. In addition, the use of a consistent investigation approach between buildings and sites will provide comparable data sets that support an increased understanding of the factors contributing to vapor intrusion impacts.

It is important to note that the recommended approach for evaluation of vapor intrusion impacts may not satisfy all regulatory requirements. The many vapor intrusion guidance documents currently available provide disparate and sometimes conflicting recommendations. The end user should review the applicable guidance and modify or supplement the recommended approach to ensure that regulatory requirements are satisfied.

7.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

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 that COCs may be migrating from a local source through SG toward a building or buildings, a field investigation is required to determine the presence or absence of vapor intrusion impacts to these specific buildings. Section 4.6 of the project Final Report provides a 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 1) applicable regulatory guidance may impose additional or different investigation requirements and 2) the understanding of vapor intrusion is evolving rapidly and recommended investigation approaches are likely to continue to evolve.

8.0 REFERENCES

Altshuler, K. B., and D. E. Burmaster (1997). “Soil Gas Modeling: The Need for New Techniques and Better Information.” Journal of Soil Contamination 6(1): 3-8.

Barber, C., G. B. Davis et al. (1990). “Factors Controlling the Concentration of Methane and Other Volatiles in Groundwater and Soil-Gas Around a Waste Site.” Journal of Contaminant Hydrology 5(2): 155-169.

Folkes, D. J., and P. S. Arell (2003). Vapor intrusion – EPA’s new regulatory initiative and implications for industry. American Bar Association’s Litigation Section, Environmental Litigation CLE Seminar, Snowmass, Colorado.

GSI Environmental (2007). White Paper: Recommendations for the Investigation of Vapor Intrusion, Version 3, Issued December 14, 2007.

Hers, I., R. Zapf-Gilje et al. (2003). “Evaluation of the Johnson and Ettinger Model for Prediction of Indoor Air Quality.” Ground Water Monitoring & Remediation 23(1): 62-76.

Johnson, P. C., and R. Ettinger (1991). “Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings.” Environmental Science and Technology 25(8): 1445-1452.

Johnson, P. C. (2002). “Identification of Critical Parameters for the Johnson and Ettinger (1991) Vapor Intrusion Model.” American Petroleum Institute 17: 1-N2.

Mathieu, G. G., P. E. Biscaye, R. A. Lupton, and D. E. Hammond. (1988) System for measurement of 222radon at low levels in natural waters. *Health Phys.* 55: 989-992.

McCarthy, K. A., and R. L. Johnson (1993). “Transport of Volatile Organic Compounds Across the Capillary Fringe.” Water Resources Research 29(6): 1675-1683.

McHugh, T. E., J. A. Connor et al. (2004a). “An Empirical Analysis of the Groundwater-to-Indoor-Air Exposure Pathway: The Role of Background Concentrations in Indoor Air.” Environmental Forensics 5: 33 - 44.

McHugh, T. E., J. A. Connor et al. (2004b). “Discussion of ‘Evaluation of the Johnson and Ettinger Model for Prediction of Indoor Air Quality.’” Ground Water Monitoring & Remediation 24(2): 139-140.

McHugh, T. E., J. A. Connor et al. (2003). A Groundwater Mass Flux Model for Groundwater-to-Indoor-Air Vapor Intrusion Seventh International In Situ and On-Site Bioremediation Symposium, Orlando, FL; June 2-5, 2003, Battelle Press, Columbus, OH.

McHugh, T. E., P. C. DeBlanc et al. (2006). “Indoor Air as a Source of VOC Contamination in Shallow Soils Below Buildings.” Soil and Sediment Contamination 15(1): 103-122.

McHugh T. E., D. E. Hammond, T. Nickles, and B. Hartman (2008). “Use of Radon Measurements for Evaluation of VOC Vapor Intrusion,” Environmental Forensics, 9(1): 107-114.

Parker, J. C. (2003). “Modeling Volatile Chemical Transport, Biodecay, and Emission to Indoor Air.” Ground Water Monitoring & Remediation 23(1): 107-120.

Richardson, G. M. (1997). “What research is needed on the indoor infiltration of volatile organic contaminants?” Journal of Soil Contamination 6(1): 1-2.

Roggemans, S., C. L. Bruce et al. (2001). Vadose Zone Natural Attenuation of Hydrocarbon Vapors: An Emperical Assessment of Soil Gas Vertical Profile Data, American Petroleum Institute: 1-12.

USEPA (2000). User's Guide For The Johnson And Ettinger (1991) Model For Subsurface Vapor Intrusion Into Buildings (Revised). Office of Emergency and Remedial Response.

USEPA (2001). Supplemental Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathways, Draft for Comment. Office of Solid Waste.

USEPA (November 29, 2002). “Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance).” Retrieved November 11, 2003, from http://www.epa.gov/epaoswer/hazwaste/ca/eis/vapor.htm.

USEPA (2004). A Citizen’s Guide to Radon: The Guide to Protecting Yourself and Your Family From Radon (Revised). Indoor Environments Division.

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