# Innovative Methods for Vapor Intrusion Investigation, Risk Assessment, and Mitigation Monitoring

**Robert W. Scrafford, P.E. and Kenneth T. Guttman, P.E.**
Gannett Fleming, Inc., 7133 Rutherford Road, Suite 300, Baltimore, MD 21244

## ABSTRACT

Since 2002, a significant petroleum vapor intrusion investigation and mitigation has been conducted in the District of Columbia, where several hundred soil vapor, sub-slab, indoor air, and ambient air samples were collected from a residential neighborhood. Several innovative methods of investigation, risk assessment, and mitigation were conducted to better predict property-specific vapor intrusion issues and to conduct vapor mitigation in a less intrusive manner. Soil vapor, ambient air, and indoor air samples were collected for radon to determine a slab-specific attenuation factor that was not influenced by background concentrations of contaminants. From these data, a realistic contribution to vapor intrusion by any contaminant present in soil vapor can be estimated. An innovative method to estimate vapor intrusion risk for residences with a water table at or near the basement slab was developed and accepted by the U.S. Environmental Protection Agency as part of a Baseline Human Health Risk Assessment. Lastly, an innovative sub-slab depressurization design was implemented to measure cross-slab pressure differential pressure and collect indoor and sub-slab samples from outside the residence so that the system could be monitored without technicians entering the home.

## INTRODUCTION

Most large-scale vapor intrusion projects progress through several stages during their lifecycle. Initially, the potential for vapor intrusion to occur is investigated, followed by a risk assessment if the vapor intrusion pathway is complete, proceeding to mitigation if risk thresholds are exceeded. Innovations were developed during each of these lifecycle stages to overcome problems that were presented to the project team.

### Investigation Phase

During the investigation phase, background sources of contamination can confound evaluations of vapor intrusion[1, 2]. Indoor use of cleaning products, household products, smoking, furniture, and even materials from which buildings are constructed can all contribute contaminants to indoor air[1]. Similarly, ambient (outdoor) air infiltration into a building can also confound vapor intrusion assessments, particularly in urban areas[3]. Additionally, it has been shown that indoor air can be a source of contaminants to shallow soil vapor beneath buildings if the residence is pressurized relative to the subsurface[4]. This is particularly problematic for petroleum sites because vapor intrusion investigations typically focus on contaminants (e.g., benzene) that are ubiquitous in household products, cigarette smoke, and ambient air.

McHugh, et al.[5] proposed a solution to this issue by using radon gas as a conservative tracer. By measuring the radon concentration in sub-slab soil vapor, indoor air, and ambient air, a slab-specific attenuation factor can be calculated that is not affected by background chemical concentrations. From these results, indoor air concentrations of site-related contaminants can be predicted from vapor intrusion alone to provide realistic exposure point concentrations for risk assessment or comparison to indoor air regulatory standards.

## Risk Assessment Phase

The Johnson and Ettinger (J&E) model as modified by the U.S. Environmental Protection Agency[6] has been adopted as the industry standard fate and transport model for assessment of vapor intrusion to indoor air when soil vapor concentrations have been measured. The model has several limitations, one of which is that it may not be applicable when contaminated groundwater is less than 5 feet below the basement slab. This is problematic because the foundation of many buildings intercepts groundwater for at least part of the year.

A novel model based on equations that describe the advective and diffusive transport of soil vapor in the vicinity of a building was developed for cases where the J&E model was not considered valid. The model assumes that a “cloud” of soil vapor envelops the portion of the residence located below ground surface and uses building-specific characteristics and soil vapor concentrations to estimate the total mass of contaminant entering a particular building.

## Vapor Mitigation Phase

If the risk assessment indicates that unacceptable risks to building occupants are present, the next step is to provide mitigation. For residential buildings, the industry standard method for vapor mitigation is considered to be sub-slab depressurization (SSD). This method involves using a fan to induce a negative pressure gradient beneath the building slab such that contaminated soil vapor is drawn from beneath the building, thereby preventing exposure to building occupants.

It is common for responsible parties to be required to prove that the SSD system is functioning as designed. One of the definitive ways to determine whether the system is producing a negative pressure gradient below the building slab is to measure the cross-slab pressure differential[7, 8]. According to the American Society for Testing and Materials[8], the cross slab pressure differential (sub-slab pressure versus outdoor air pressure) should be sufficiently negative to overcome seasonal variations in building pressurization (i.e., the stack effect). However, measuring this parameter on a routine basis is problematic because it requires multiple entries into the residence to access sub-slab probes. Many residents are not willing to allow frequent entry to their residence. A sub-slab probe connected to gas-tight tubing that extended through the foundation wall was constructed so that entry to the residence for measurements was not required.

# USE OF RADON TO MODEL INDOOR AIR CONCENTRATIONS

Radon was used as a conservative tracer to assess the potential for soil vapor intrusion because it is a naturally-occurring radioactive isotope that is not found in household products. Therefore, its presence in indoor air is a direct result of either soil vapor intrusion or ambient air intrusion. Because the contribution from ambient air can be measured and corrected for, a slab-specific accurate attenuation factor can be calculated.

## Experimental Methods

Grab samples of indoor, ambient, and sub-slab were collected for analysis of radon gas from three residences underlain by a hydrocarbon groundwater plume. Because the basements had a small footprint (approximately 500 square feet) only one sub-slab implant was installed in each residence. The sampling methodology in McHugh et al.[5] was followed to collect the samples:

1. Collect grab sub-slab soil vapor samples for the volatile compound(s) of interest using gas-tight compression fittings. Purge the sample train of ambient air prior to sampling and perform a leak check.

2. Connect a dedicated gas-tight disposable syringe to the sample train and fill a 1-liter Tedlar® bag was with approximately 100 milliliters (mL) of sub-slab air. Note the exact time of sample collection of all samples to aid in subsequent decay correction calculations.

3. Collect ambient and indoor air radon samples using a dedicated gas-tight disposable syringe and discharge directly to Tedlar® bags. A volume of approximately 300 mL should be collected as these samples contain a lower concentration of radon and more volume is required for analysis.

The samples were shipped by overnight courier and analyzed by Dr. Douglas Hammond's laboratory at the University of Southern California using an alpha scintillation counting technique in accordance with U.S. EPA methodology[9]. The laboratory corrected the results for radioactive decay between the time the sample was collected and the time of analysis.

## Calculation of Attenuation Factors

The radon results were used to calculate a slab-specific attenuation factor for radon gas intruding through the basement slab and into the basement. The attenuation factor (α) is the ratio of indoor air radon concentration attributed to soil vapor entry (corrected for ambient air intrusion) to the sub-slab soil vapor radon concentration and is calculated using the following relationship[10]:

**Equation 1.** Attenuation factor equation.

$$\alpha = \frac{C_{Rn}(indoor) - C_{Rn}(ambient)}{C_{Rn}(subslab)}$$

where:

$C_{Rn}$ = radon concentration

The calculated slab-specific attenuation factors were 4.6 x $10^{-2}$, 1.6 x $10^{-4}$, and 4.9 x $10^{-4}$ which was similar to those reported in the literature[10, 11]. As reported by others[5], all measured attenuation factors were lower than the default value of $10^{-1}$ in the U.S. Environmental Protection Agency's Draft Subsurface Vapor Intrusion Guidance[3].

## Modeling Indoor Air Concentrations

Volatile organic compounds in soil vapor behave similarly to radon[11], therefore, the attenuation factor α can be used to estimate air indoor concentrations resulting from soil vapor intrusion. The following equation was used to predict indoor air concentrations for hydrocarbons resulting from soil vapor intrusion[6]:

**Equation 2.** Prediction of indoor air concentrations of contaminants of concern.

$$C_{indoor} = \alpha(C_{subslab})$$

where:

$C_{indoor}$= the concentration of the contaminant of concern in indoor air

$C_{subslab}$= the concentration of the contaminant of concern in sub-slab soil vapor

Based on this evaluation, the contribution of compounds in sub-slab soil vapor to indoor air can be predicted without regard to background concentrations of the contaminant in indoor air. The predicted concentrations can then be used as exposure point concentrations in risk assessment.

## USE OF THE VAPOR CLOUD MODEL

The J&E model is not considered valid when contaminated groundwater is close to (less than approximately 5 feet) beneath the basement slab. The J&E model assumes that an uncontaminated capillary fringe and vadose zone are present below the slab such that the soil vapor is in equilibrium with the contaminants in the groundwater[6]. If the capillary fringe intercepts the slab, a clean vadose zone would not be present below the slab. This violates the tenets of the J&E model.

Contrary to the J&E model, the vapor cloud model can be used when contaminated groundwater is close to or intercepts the basement slab[12]. It neglects biodegradation and assumes that the measured soil vapor concentrations, collected either adjacent to or below the building slab, directly enter the building via advection or diffusion through cracks in the basement slab and walls. A paper providing the details and equations used in the vapor cloud model will be published in 2011[12].

Approximately 20 residences at a project site were located such that the capillary fringe or the groundwater table itself intercepted the basement slab. Because the vapor cloud model assumes that vapors envelop the entire portion of the residence below ground, soil vapor samples were collected adjacent to the basement foundation walls at two levels, one at or near the basement slab elevation and another at an elevation halfway between the slab and the ground surface. Soil vapor samples were collected using the Geoprobe® Post-Run Tubing methodology including a leak detection check.

In our case, the soil vapor samples collected adjacent to the slab were used to estimate indoor air concentrations for hydrocarbons measured in soil vapor using the vapor cloud model. These concentrations were used as exposure point concentrations in a risk assessment. After a thorough evaluation and discussion with U.S. EPA Region 3 risk assessors, the vapor cloud model was accepted.

## INNOVATIONS IN VAPOR MITIGATION SYSTEM MONITORING

A SSD system must overcome seasonal and temporal variations in pressure within the building, including HVAC system changes, wind load against the building, barometric pressure changes, and temperature changes[7]. The most persistent and significant threat to the functionality of the SSD system is the seasonal change called the stack effect. During the heating season, warm air within a building rises, depressurizing the building relative to the subsurface. Sub-slab soil vapor is pulled through cracks in the slab into the building. A SSD system should be designed such that the negative pressure field below the slab extends to the extents of the slab with sufficient force to overcome the stack effect. Depressurization goals vary, but sub-slab to barometric differential pressures ranging from -0.020 to -0.035 inches of water column (5 to 9 pascals) measured at the extents of the slab are considered adequate to overcome building pressure variations[7, 8].

One of the best ways to prove that an SSD system is maintaining the proper pressure field extension is to verify that the cross-slab differential pressure measured at a location farthest away from the location of the SSD slab penetration are more negative than the depressurization goal. This is accomplished by installing a sub-slab implant near an exterior wall. In our residential situation, frequent entries of the residence for monitoring were avoided by connecting the sub-slab implant to gas-tight tubing that extended through the exterior wall of the building.

## Sub-Slab Implant Apparatus Construction

The implant apparatus was constructed of 1/4-inch outside diameter, 1/8-inch inside diameter 316 stainless steel tubing for durability. Elbows and other fittings were stainless steel gas-tight compression fittings manufactured by Swagelok®. Figure 1 provides a schematic of the sub-slab implant apparatus. Figures 2 and 3 are as-built photographs.

**Figure 1**: Sub-slab Implant Apparatus Schematic in Cross Section

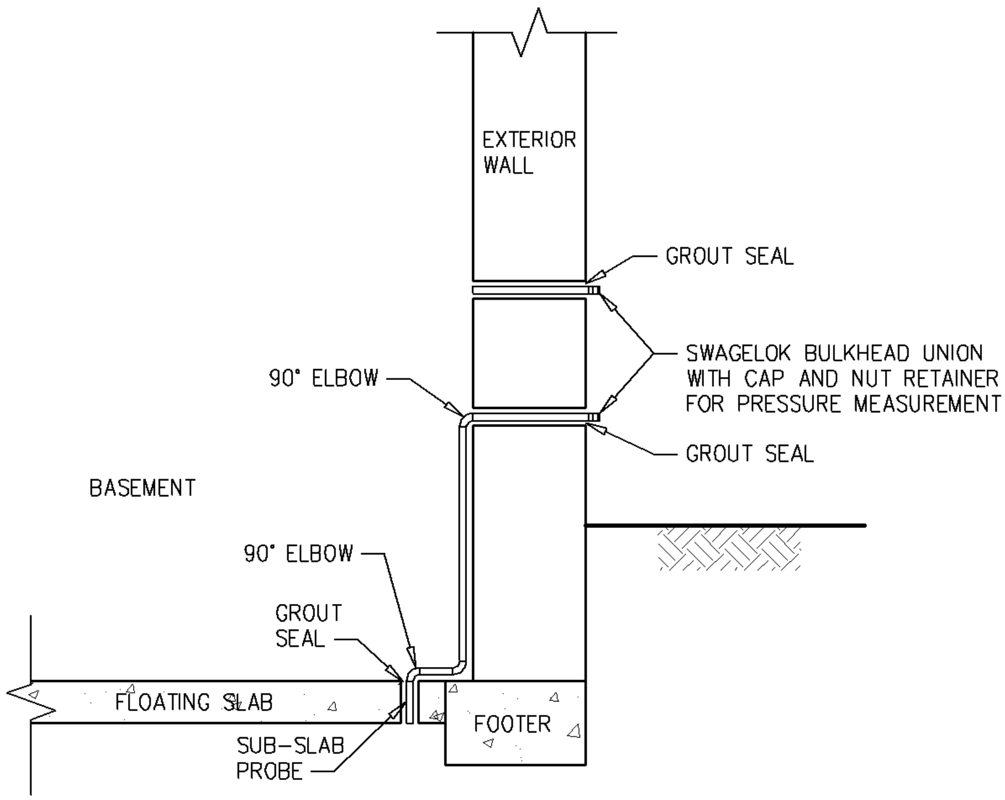

**Figure 2**: Interior view of Sub-slab Implant Apparatus (right) and indoor air probe (left)

**Figure 3**: Exterior view of Sub-slab Implant Apparatus (left) and indoor air probe (right)

Several steps were undertaken when installing the implant(s). They were installed in unobtrusive areas that received little traffic from the resident to maintain the integrity of the implant.

- When drilling the hole for the sub-slab portion of the implant apparatus, care was exercised to avoid the building footer. Several pilot holes may be required to determine its location.

- Prior to installation, the entire implant apparatus was constructed and a vacuum check conducted to ensure all compression fittings were adequately tight and no leaks were evident.

- The apparatus was installed in one piece, threading it through the exterior wall on one end and through the slab on the other end.

- The annulus surrounding the tubing inserted through the slab was sealed with hydraulic cement, while the tubing inserted through the building wall was sealed with hydraulic cement or caulk depending on the composition of the building sheathing.

- Brackets were required to secure the vertical run of tubing to the interior wall for stability.

- The fitting on the exterior of the building was capable of connecting to the tubing of monitoring equipment without leaks. A nut retainer was installed on this fitting to avoid spinning the tubing when removing the threaded cap.

- Once installation was complete, a second leak check using a conservative tracer (e.g., helium) could be conducted to quantify leakage. The authors did not conduct this check. If the leak percentage is not acceptable, the apparatus can be repaired at this point. If the leak check is completed, future sub-slab soil vapor monitoring from the apparatus may be considered, depending on the data quality objectives of the project.

- To monitor the ratio of indoor to outdoor building pressure, a second implant was installed through the exterior wall only. If interior air flow to this implant is not obstructed (i.e., the basement is without interior walls) and the implant is sealed properly, indoor air sampling through the implant from the exterior of the residence may be considered, depending on the data quality objectives of the project.

## Cross-Slab Differential Pressure Testing

Once the sub-slab implant is installed and the seal verified, cross-slab differential pressures can be monitored. The differential pressures measured are very low and require specialized equipment. An Omniguard™ 4 differential pressure recorder capable of measuring differential pressures from 0.25 to -0.25 inches of water column (62 to -62 pascals) was used to take the measurements.

The following table summarizes a pressure field extension test conducted through the external probe at one residence. The SSD system sump was located approximately 30 feet from the sub-slab probe. The SSD system was left off for a period of several days prior to the test.

**Table 1.** SSD Pressure Field Extension Test

| Time | SSD System Status | Differential Pressure (inches of water column) |
|---|---|---|
| 0751 | Off | -0.010 |
| 0814 | Off | -0.011 |
| 0816 | On | -0.038 |
| 0820 | On | -0.037 |
| 0825 | On | -0.035 |
| 0830 | On | -0.039 |

The differential pressure across the slab was weakly negative prior to turning on the SSD system. The system was turned on via an external switch at time 0815 and within one minute was operating at the upper range of the depressurization goal. This indicates that the SSD system is functioning as designed and an adequate pressure field extends to the extents of the building slab, preventing vapor intrusion. Maintenance of the depressurization goal over time, particularly during the heating season, can be verified from outside the residence through the implant apparatus with little disturbance to the resident.

The differential pressure measurements in Table 1 were not corrected for friction losses in the tubing. Future research into this subject will determine if the losses are negligible. However, as long as the depressurization goal is met, vapor intrusion is precluded.

## SUMMARY

Several problems were presented to a project team during the lifecycle of a large vapor intrusion project. The project team produced innovations in vapor intrusion investigation, risk assessment, and mitigation to solve the issues and complete the project to the satisfaction of the regulators.

During the investigation phase of the project, the conservative tracer radon gas was used to estimate slab-specific attenuation factors for three residences. The attenuation factors ranged from $4.6 \times 10^{-2}$ to $4.9 \times 10^{-4}$, within the range reported by others. The attenuation factors were then used to predict the indoor air concentration of chemicals within the residences without concern for the confounding effects of background concentrations.

During the risk assessment phase, indoor air concentrations for several residences were not able to be modeled using the J&E model because the depth to groundwater below the basement slab was less than 5 feet. The conservative vapor cloud model was developed, which assumes that the entire portion of the building below ground was enveloped by a “cloud” of soil vapor. The model used soil vapor concentrations to estimate indoor air exposure point concentrations for use in a baseline risk assessment that was accepted by the U.S. Environmental Protection Agency.

Residents receiving vapor mitigation SSD systems were not enthusiastic about multiple visits to their residence for monitoring. An innovative apparatus for measuring cross-slab differential pressure from outside the residence was developed and tested to ensure that the SSD system was functioning as designed.

## ACKNOWLEDGEMENTS

The authors wish to thank Dr. Douglas Hammond of the University of Southern California for analyzing soil vapor samples and Dr. Thomas McHugh of GSI Environmental, Inc. for information regarding methodology for collecting radon samples and differential pressure measurements. Helpful comments were received from several peer reviewers, including Sid Curran and Paula Loht.

## REFERENCES

1. McHugh, T.; Connor, J.; Ahmad, F.; *Env. Forensics.* **2004**, 5, 33-44.

2. Hodgson, A.; Levin, H.; *Volatile Organic Compounds in Indoor Air: A Review of Concentrations Measured in North America Since 1990;* Lawrence Berkley National Laboratory, Berkley, CA, 2003; Report LBNL-51715.

3. U.S. Environmental Protection Agency; *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater to Soils*; Office of Solid Waste and Emergency Response, 2002.

4. McHugh, T.; DeBlanc, P; Pokluda, R.; *Soil and Sed. Contam.* **2006**, 15, 103-122.

5. McHugh, T.; Hammond, D.; Nickels, T.; Hartman, B.; *Env. Forensics.* **2008**, 9, 107-114.

6. U.S. Environmental Protection Agency; *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings;* Office of Emergency and Remedial Response; 2004; See http://www.epa.gov/oswer/riskassessment/airmodel/pdf/2004_0222_3phase_users_guide.pdf (accessed May 2010).

7. U.S. Environmental Protection Agency; *Engineering Issue: Indoor Air Vapor Intrusion Mitigation Approaches;* Office of Research and Development; 2008; EPA/600/R-08-115.

8. *Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings*; ASTM International; West Conshohocken, PA, 2003; Standard E 2121-03.

9. U.S. Environmental Protection Agency; *Indoor Radon Decay Product Measurement Device Protocols*; 1992; EPA 402-R-92-004.

10. Fischer, M.; Bentley, A.; Dunkin, K.; Hodgson, A.; Nazaroff, W.; Daisey, J.; *Environ. Sci. Technol*. **1996**, 30, 2948-2957.

11. Little, J.; Daisey, J.; Nazaroff, W.; *Environ. Sci. Technol*. **1992**, 26, 2058-2066.

12. Salhotra, A.; Sambana, V.*; Vapor Cloud Model to Estimate Sub-Slab to Indoor Air Attenuation Factor; 2011;* Submitted for presentation at the Association for Environmental Health and Sciences Conference on Soils, Sediments, Water, and Energy; March 2011.

## KEY WORDS

Radon
Risk Assessment
Vapor mitigation
Attenuation factor