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# Use of Radon Measurements for Evaluation of Volatile Organic Compound (VOC) Vapor Intrusion

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We have utilized a simple method for the collection of gas samples from vapor intrusion investigation sites and the analysis of radon concentrations at an offsite laboratory. The radon data can be used to evaluate the movement of soil gas through building foundations at sites contaminated with volatile organic compounds (VOCs) where vapor intrusion is a concern. The use of radon as a tracer for the movement of soil gas into buildings minimizes the problem of indoor sources associated with the direct measurement VOCs. We have used this method to measure indoor to sub-slab attenuation factors in six buildings with the resulting values ranging from 0.0002 to 0.006 (dim). These values are similar to radon attenuation factors reported by other researchers, but are much lower than default values for VOCs recommended in regulatory guidance (United States Environmental Protection Agency [USEPA], 2002). The vertical radon concentration profile in soil gas can be used to evaluate soil gas mixing with the atmosphere to support the collection of soil gas samples for VOC analysis adjacent to, rather than below, a building.

Keywords: vapor intrusion, radon, soil gas, attenuation

## Introduction

Since 2000, regulators and the regulated community have become increasingly concerned with the potential hazards of vapor intrusion, the migration of volatile organic compounds (VOCs) from contaminated soil or groundwater to indoor air. Detailed investigations at a number of corrective action sites have documented elevated levels of chlorinated VOCs in houses located above contaminated groundwater (Tillman and Weaver, 2005; DiGiulio et al., 2006). In response, the United States Environmental Protection Agency (USEPA) and many state regulatory agencies have issued guidance specifying screening and field investigation procedures for the identification of vapor intrusion impacts at corrective action sites. Due to the limited understanding of the site-specific factors that contribute to vapor intrusion impacts, screening criteria for this pathway are very conservative and most of the guidance documents rely primarily on the use of field investigations for the identification of the vapor intrusion impacts.

In its current form, the USEPA *Subsurface Vapor Intrusion Guidance* (USEPA, 2002) recommends a tiered approach for evaluation of the vapor intrusion pathway at corrective action sites consisting of: 1) preliminary pathway identification

based on the presence of a source of volatile compound and a receptor (i.e., a building), 2) an evaluation of volatile compound concentrations using generic screening concentrations and “semi-site-specific” screening concentrations (i.e., screening concentrations based on a limited set of site-specific factors), and 3) a site investigation to evaluate vapor intrusion by direct measurement. Generic and semi-site-specific screening concentrations included in the USEPA guidance have been developed using conservative subsurface-to-indoor air attenuation factors. For chemicals for which the groundwater screening concentrations based on these default attenuation factors are below the drinking water maximum contaminant levels (MCLs), the screening concentrations included in the guidance document have been set equal to the MCL (USEPA, 2002). For a number of common VOCs such as trichloroethene (TCE) and benzene, both the generic and the semi-site-specific groundwater vapor intrusion screening limits are equal to MCL (i.e., 5 µg/L for these two chemicals). As a result, a majority of corrective action sites where USEPA guidance is applied will have VOC concentrations in groundwater exceeding these screening concentrations and will require field-based site investigations to evaluate the potential for vapor intrusion impacts. However, site-specific evaluations of potential vapor intrusion, particularly those involving the measurement of indoor air VOC levels, can prove to be highly problematic due to the presence of common indoor sources of VOCs already present within buildings, resulting in average background indoor air concentrations for some common VOCs that exceed USEPA screening concentrations for indoor

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air (McHugh et al., 2004). Therefore, for VOCs associated with common indoor sources, the direct measurement of concentrations in indoor air is often not an effective method for identifying vapor intrusion impacts.

Measurement of sub-slab soil gas concentrations is a preferred approach by some regulatory agencies, but the actual transport rate of the soil gas into the overlying structure is site specific (McHugh et al., 2006). Hence, there is uncertainty in what concentrations pose a real threat to indoor air quality. Radon is a naturally occurring compound in soil gas for which vapor intrusion is usually the primary source in indoor air (Arvela et al., 1988). In contrast to VOCs, indoor sources generally contribute little to the indoor radon concentration. As a result, the measurement of radon concentrations in soil gas and indoor air may be a useful tool for the evaluation of sites with potential VOC vapor intrusion impacts (Mosley et al., 2004) as it allows determination of soil gas transport through the building foundation.

Uranium is present in all soils, with concentrations that are typically a few parts per million (ppm). Radon-222 is an intermediate isotope in the uranium-238 decay chain and the decay of uranium in soil results in the emission of radon into the pore space of all soils. Radon-222, itself, decays with a half-life of 3.84 days, leading to its loss from soil gas. As a result, in the absence of gas exchange with the atmosphere, the steady-state radon concentration (in activity, disintegrations/m<sup>3</sup>-time) in soil gas is equal to the emission rate over the decay rate:  $C_{\text{radon}} = E/\lambda$ , where  $E$  is the emission rate per unit volume of pore gas (pCi/m<sup>3</sup> d) and  $\lambda$  is the radon decay constant (0.18/d). Tanner (1980) provided a comprehensive review of this process, noting the importance of factors including uranium concentration, grain size, soil moisture, and organic content in controlling emissions. The radon concentration in soil gas varies by location depending primarily on the uranium concentration in soil, the soil porosity, and the soil moisture.

Although radon vapor intrusion is considered to be most problematic in parts of the country with the highest soil gas radon levels, all regions contain measurable concentrations of radon in the soil gas. The radon concentration in typical soils ranges from 240 to 2400 pCi/L (Swedjemark, 1986; Little et al., 1992) and is much higher than atmospheric radon concentrations (0.2–0.7 pCi/L; USEPA, 1993). As a result, radon has the potential to serve as a naturally occurring tracer for soil gas entry into buildings at most corrective action sites around the country.

To use radon as a tracer for soil gas entry into a building, the radon concentration must be measured below, inside, and outside of the building. These measurements allow for the calculation of a building-specific attenuation factor that describes the dilution of radon from the soil gas to indoor air. Although there are three inexpensive and widely used methods to measure indoor radon concentrations (charcoal canisters, electrets, and alpha-track detectors), all of these methods require long-term (48 h to 3 months) exposure durations. None of the methods are suitable for measurement of radon concentrations in soil gas below buildings because the measurement devices are relatively large and cannot

easily be placed below a building foundation for the required sampling period. In addition, the high moisture levels in soil gas interfere with the sorption of radon onto charcoal canisters, and the gaseous diffusion constant in the vadose zone is unknown. As a result, grab soil gas samples are the most effective means to measure radon concentrations in soil gas.

In this article, we present several applications where radon was used to provide an improved understanding of VOC vapor intrusion. We utilized a simple method established by the USEPA for the collection of gas samples and analysis of radon concentrations (USEPA, 1992). This evaluation procedure provides a low-cost and widely applicable method to evaluate the movement of gas from shallow soils into buildings without the confounding problem of background indoor sources common to many VOCs.

## Experimental Section

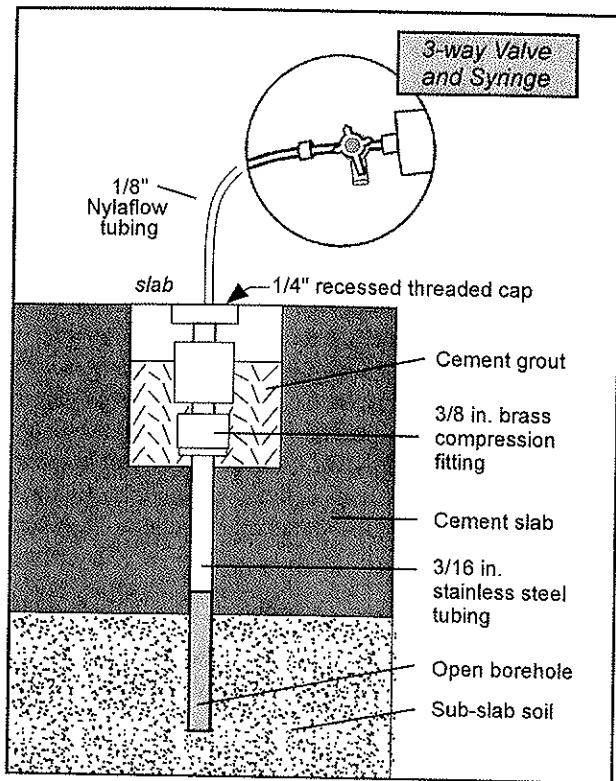
### *Installation of Sub-Slab Sampling Ports*

Samples of soil gas from below the building foundation can be collected through any sampling point that provides a tight seal across the foundation. DiGiulio et al. (2006) have described a commonly used sample point.

### *Sample Collection and Storage*

Gas samples can be collected using a polypropylene syringe (60 cc or larger volume is preferred) with a butyl rubber or other gas-tight plunger. Holding time in this type of syringe should be less than 30 min, as radon can diffuse through the syringe walls. Storage tests indicate the radon loss rate from polypropylene syringes is approximately 50%/day (data not shown). Different syringes should be used to collect samples with high (below foundation) and low (indoor air) concentrations because some radon may adsorb to the walls of the syringe, resulting in cross-contamination between samples. For below-foundation samples, the syringe can be attached to the sampling point using a sampling train as illustrated in Figure 1. The sampling point and sampling train have a combined volume of less than 5 mL. Prior to sample collection, 10–20 mL of gas are typically purged from the system, resulting in purging of several line volumes with minimal disturbance of the sub-slab soil gas. For indoor or ambient samples, the syringe can be filled directly and sealed with a polycarbonate stopcock.

The samples can be transferred from the syringe to a Tedlar bag (SKC Inc., PA) or other gas-tight container for storage and shipment prior to analysis. Approximately 100–300 cc of sample can be injected into an empty Tedlar bag (0.5 L) fitted with a polypropylene fitting. These bags are manufactured from DuPont PVF film, by several suppliers. Because samples can be depressurized during air shipment, no more than 300 mL of gas should be collected in a 500-mL bag. Some care should be used



**Figure 1.** Sub-slab sample point and sampling train used to collect sub-slab gas samples for radon analysis. Sample point components adapted with permission from DiGiulio, D., Paul, C. Cody, R., et al. 2006. *Assessment of Vapor Intrusion in Homes Near the Raymark Superfund Site Using Basement and Sub-Slab Air Samples*. USEPA Office of Research and Development, EPA/600/R-05/147, March 2006.

in handling these bags, as they can abrade and develop pinhole leaks if ground against rocks or sandy soils.

Choosing an appropriate storage container is critical, as radon diffuses into and through many types of rubbers and plastics. Others have reported very low radon loss from Mylar (Sievers Instruments, Boulder, CO), aluminized Mylar, or Tedlar bags (USEPA, 1992). We have confirmed these findings through laboratory storage tests using Tedlar bags (Table 1) and evacuated counting cells, glass vials, Summa canisters, and aluminized Mylar bags (data not shown). Loss of radon from the storage containers appears to be negligible for periods of at least 8–10 days.

In addition, we have compared evacuated counting cells, glass vials through the collection of field replicate samples in these containers (Table 2). For this analysis, replicate grab samples were collected using evacuated counting cells and evacuated glass vials. Both sample containers were shipped to the laboratory by overnight express delivery. The counting cells were analyzed directly while the gas in the glass vials were transferred to separate counting cells in the laboratory for analysis. Both sample collection and storage containers yielded comparable results.

Also, for some indoor samples, a 48-h charcoal canister sample was also collected. For these samples, the charcoal canister was placed at the sample location for 48 h in accordance with the

**Table 1.** Storage tests of field samples

Sample ID	Container	Holding time (days)	Activity* (pCi/L)	SSD** (%)	2nd/1st
U5 8007.900A	Tedlar	1.48	479 ± 13	2.6	1.04
		10.04	497 ± 20		
QC-L	Tedlar	2.02	670 ± 17	2.6	1.04
		10.03	695 ± 21		
U5 8007.901	Tedlar	1.50	122 ± 7	8.0	0.89
		10.44	109 ± 5		
T12-1-091305	Tedlar	1.03	243 ± 6	4.5	1.07
		11.15	259 ± 5		
T11-1-091395	Tedlar	1.04	287 ± 7	3.3	0.95
		11.15	274 ± 5		
Mean	Cali 5	1.03	287 ± 7	1.5	0.98
		11.15	281 ± 5		

\*Decay corrected based on radon decay constant of 0.1803 day<sup>-1</sup>. Uncertainty based on counting statistics only. \*\*SSD is one sample standard deviation of the duplicates for each bag.

manufacturer's instructions and then shipped to Accustar Labs (Medway, MA) for analysis. As discussed in the introduction, the charcoal canisters are not suitable for soil gas analyses due to the high moisture levels in soil gas. For the indoor air samples, however, the analytical results from the charcoal canisters were similar to those for the gas grab samples, with no consistent bias observed. All of the tested sample containers appear to provide satisfactory performance for sample collection and storage for up to a week. However, Tedlar bags were most convenient because they are widely available, easy to handle, and their flexibility keeps pressure at ambient when samples are withdrawn for analysis in the laboratory.

*Sample Analysis*

Radon concentrations in the collected gas samples were measured using alpha scintillation counting in accordance with established USEPA protocols (USEPA, 1992). In the laboratory, an aliquot of gas was withdrawn from the sample container into a syringe with a butyl rubber plunger, equipped with a two-way

**Table 2.** Comparison of sample collection containers for analysis of radon in gases\*

Sample location	Activity (pCi/L)		
	Evacuated counting cell	Glass vial	Charcoal canister
Hill AFB Res. #1 Indoor 2	0.16	0.21	<0.4
Hill AFB Res. #1 Indoor 4	0.29	0.4	0.4
Hill AFB Res. #1 Sub-slab 1	746	636	—
Hill AFB Res. #2 Indoor 1	0.25	0.33	0.4
Hill AFB Res. #2 Sub-slab 3	156	149	—
Hill AFB Res. #2 Soil Gas 5	701	629	—

\*Note: Charcoal canisters were analyzed by Accustar Labs (Medway, MA) using the United States Environmental Agency (USEPA) Method #402-R-93-004 079. Analytical precision for the other methods is the larger of ±4% or ±0.10 pCi/L.

polycarbonate stopcock. If the sample was drawn from a rigid container, then the pressure in the syringe was less than ambient, and the syringe stopcock was closed after drawing the sample, the plunger pushed in to raise pressure above ambient, the stopcock opened to allow pressure to reach ambient, and then closed while the sample volume was read. The sample was passed through a drying column of CaSO<sub>4</sub> into a pre-evacuated Lucas-type counting cell (Lucas, 1957; Mathieu et al., 1988). The counting efficiency for each cell was determined as a function of the density of the gas in the counting cell (Sarmiento et al., 1976).

## Results and Discussion

### Comparison of Radon and Volatile Organic Compound Attenuation

We have used the analysis procedures described previously to measure radon concentrations in and below two single-family residences located in Utah and one small office building located in Oklahoma (Table 3). These measurements have been used to compare radon migration through the building foundation to VOC migration. For these three buildings, ambient, indoor, and below-foundation radon and below-foundation VOC samples were collected as grab samples while the ambient and indoor VOC samples were 24-h composites. For each sampling event, samples were collected from three separate locations within each medium (i.e., ambient, indoor, and below-foundation) and the results are reported as the average  $\pm$  the standard deviation for the three sample locations. The standard deviation is typically higher for below-foundation samples, reflecting the higher spatial variability within this medium. The VOC samples were analyzed by USEPA Method TO-15 (USEPA, 1999a) with selective ion monitoring used for the indoor and ambient samples in order to obtain the lowest possible detection limits. We did not change or control building operating conditions during sam-

ple collection and we allowed the building occupants to conduct their normal activities. The impact of chemicals from soil gas on indoor air quality is often expressed in terms of an attenuation factor, which is defined as the ratio of the measured concentration of the volatile chemical of concern (for example, benzene) in indoor air ( $C_b$ ; corrected by subtracting the ambient air concentration) divided by the measured concentration of the chemical in soil gas ( $C_s$ ; i.e.,  $AF = C_s/C_b$ ) (Interstate Technology & Regulatory Council [ITRC], 2007). For stable compounds without indoor sources, the concentration of soil-sourced chemicals in a building depends on the rate of gas inflow from the soil ( $Q_s$ ) relative to the total ventilation rate in the building ( $Q_b$ ). As a result, a measured attenuation factor reflects the ratio of gas flow (advection and diffusion) through the building foundation to relative total building ventilation. However, for radioactive compounds, an additional factor must be considered to account for radioactive decay ( $\lambda$ ; 8/day for radon). The effect of radioactive decay on the attenuation factor is

$$AF = C_s/C_b = Q_s/(Q_b + \lambda V) \quad (1)$$

where  $AF$  = attenuation factor,  $C_s$  = measured concentration of the chemical in soil gas, measured concentration of the volatile chemical of concern (benzene),  $Q_s$  = gas inflow from the soil,  $Q_b$  = total ventilation rate in the building, and  $V$  = the building volume. The same equation (with  $\lambda = 0$ ) applies to a nonradioactive gas. From Eq. (1), it can be determined that the relationship between the attenuation rate for a non-radioactive gas ( $AF_{NR}$ ) and the attenuation factor for a radioactive gas ( $AF_R$ ) is

$$AF_{NR} = AF_R(1 + \lambda ER) \quad (2)$$

where  $ER = Q_b/V$  is the building air exchange rate. In most buildings, the air exchange rate is greater than or equal to 6/day (USEPA, 2002). For a building with an air exchange rate of 6/day the attenuation factor for radon would be 3% lower than the attenuation factor for benzene (i.e., 0.181/6). This difference

Table 3. Comparison of radon and volatile organic compound concentrations at three buildings with slab foundations\*

Compound	Below-foundation soil gas	Indoor air	Ambient air	Measured attenuation factor
<i>Hill AFB, Utah Residence #1, March 2006</i>				
Radon (pCi/L)	68 $\pm$ 54 (1)	0.6 $\pm$ 0.2	0.18	0.006
TCE (ug/m <sup>3</sup> )	8.4 $\pm$ 8.6	0.075 $\pm$ 0.016	0.092 $\pm$ 0.085	NC
<i>Hill AFB, Utah Residence #2, March 2006</i>				
Radon (pCi/L)	427 $\pm$ 283	0.8 $\pm$ 0.01	0.18 (2)	0.001
TCE (ug/m <sup>3</sup> )	<0.94	0.14 $\pm$ 0.044	0.055 $\pm$ 0.017	NC
<i>Altus AFB, Oklahoma Building 418, July 2006</i>				
Radon (pCi/L)	571 $\pm$ 43	0.35 $\pm$ 0.09	0.13	0.0004
TCE (ug/m <sup>3</sup> )	50 $\pm$ 62	9.5 $\pm$ 2.2	12 $\pm$ 5.7	NC
PCE (ug/m <sup>3</sup> )	401 $\pm$ 501	0.26 $\pm$ 0.06	0.12 $\pm$ 0.03	0.0003
<i>Altus AFB, Oklahoma Building 418, December 2006</i>				
Radon (pCi/L)	702 $\pm$ 441	0.8 $\pm$ 0.1	0.3	0.0007
TCE (ug/m <sup>3</sup> )	21 $\pm$ 17	0.13 $\pm$ 0.042	0.063 $\pm$ 0.021	0.0033
PCE (ug/m <sup>3</sup> )	348 $\pm$ 283	0.42 $\pm$ 0.17	0.17 $\pm$ 0.038	0.0007

\*Note: 1) Table shows average radon activity  $\pm$  standard deviation for buildings with samples from three or more locations; and 2) radon concentration in ambient air for Hill AFB Residence #2 measured at Residence #1. NC = no attenuation factor calculated when ambient air concentration greater than indoor air concentration or when chemical is not detected below building foundation; PCE, tetrachloroethene; TCE, trichloroethene.

would be lower for buildings with higher air exchange rates. As a result, the impact of radon decay on measured attenuation factors can be neglected in typical analyses without significant error.

For the three buildings where we measured both radon and VOC concentrations, the measured radon attenuation factors ranged from 0.0004 to 0.006 with an average attenuation factor of 0.003 (Table 3). This is similar to the typical attenuation factor of 0.003 predicted by Little et al. (1992), the average radon attenuation factor of 0.004 from a study of 10 single-family houses in New York (Mosley et al., 2004), and the average attenuation factor of 0.004 from a study of 9 single-family houses in Stratford, Connecticut (DiGiulio et al., 2006). Note, however, that the radon attenuation factors for the houses in New York and Connecticut were not corrected for ambient radon concentrations. As a result, these radon attenuation factors may be biased high and therefore underrepresent the true radon attenuation at these locations.

At the two residences in Utah, TCE was a known subsurface contaminant while both TCE and PCE were detected in the subsurface at the building in Oklahoma. No VOC attenuation factors could be calculated for the two residences in Utah because ambient TCE concentrations were greater than the indoor TCE concentrations at Residence #1 and TCE was not detected below Residence #2. For the building in Oklahoma, an attenuation factor could be calculated for PCE for both sample events (i.e., July 2006 and December 2006), but for TCE an attenuation factor could be calculated only for the December 2006 sampling event because the ambient TCE concentration was higher than the indoor TCE concentration for the July 2006 event. For the Oklahoma site, the attenuation factors for PCE closely matched the attenuation factors for radon, but the attenuation factor for TCE was higher, suggesting a potential indoor source of TCE.

At all three buildings studied, the radon appeared to be a more useful tracer of soil gas movement through the building foundation than TCE. At all three buildings, the radon concentration indoors was greater than the ambient concentration. The differences were statistically significant ( $p < 0.05$ ) for all three buildings; however, given the limited data set and measurement error associated with the low radon concentrations the statistical significance may be overstated. In contrast, ambient or indoor TCE sources masked any impact of vapor intrusion on the indoor concentration of TCE at the three buildings during at least

one sampling event. The studies of single-family residences in New York and Connecticut (Mosley et al., 2004; DiGiulio et al., 2006) found that radon generally overpredicted the VOC attenuation factor (i.e., underpredict VOC attenuation); however, correction for ambient radon might have decreased or eliminated this overprediction. Taken together, the results from this study and the findings of the other researchers suggest that radon generally serves as a sensitive and conservative tracer for soil gas migration through the building foundation. Radon analyses are sufficiently sensitive to measure attenuation factors of  $< 0.001$ .

#### *Radon Measurements at Sites without Volatile Organic Compound Contamination*

Because radon is present in all soil gas, radon can be used to evaluate soil gas migration into buildings even at sites not impacted by VOCs in the subsurface. This can be useful for understanding the susceptibility of certain building types or geographical areas to vapor intrusion. In addition, the measurement of radon attenuation factors can be used to better characterize the range of attenuation factors observed between buildings, supporting the selection of upper-bound attenuation factors for vapor intrusion pathway screening.

We measured radon concentrations at five residences in Houston, TX, without known VOC impacts in the subsurface and at one school building with chlorinated VOCs present in groundwater but not detected below the building foundation (Tables 4 and 5). Two of the residences and the school had slab foundations while the other three residences had pier and beam foundations. In Houston (and many Gulf Coast areas), houses with pier and beam foundations sit 2–3 ft above the ground surface with a dirt floor crawl space separating the structure from the at-grade soils. The crawl space is typically ventilated through small openings located on the walls around the perimeter of the crawl space.

For the three slab-on-grade buildings, the radon attenuation factors (0.0002–0.0003) were at the low end of the range of attenuation factor values reported for residences in other areas (Table 4). For the three pier and beam residences studied, the crawl space radon concentration was only 1.2–2.6 times the ambient radon concentration (Table 5). Although we did not measure the soil gas radon concentration at the pier and beam houses, we assumed that the concentrations were similar to the

**Table 4.** Measured radon concentrations in soil gas, indoor air, and ambient air for slab-on-grade buildings in Houston, Texas\*

Sample location	Activity (pCi/L)			
	Below foundation soil gas	Indoor air	Ambient air	Attenuation factor**
Houston, TX, Residence #1	649 +/-296	0.44 +/-0.11	0.33	0.0002
Houston, TX, Residence #2	1283 +/-382	0.50 +/-0.10	0.12	0.0003
Houston, TX, Private School	482	0.16	—	0.0003

\*Average radon activity +/-standard deviation for buildings with samples from three or more locations. \*\*Attenuation factor for private school building not corrected for radon concentration in ambient air.

**Table 5.** Measured radon concentrations in crawl space and ambient air for pier and beam houses in Houston, Texas

Sample location	Activity (pCi/L)	
	Crawl space air	Ambient air
Houston, TX, Residence #3	0.41	0.33
Houston, TX, Residence #4	0.31	0.12
Houston, TX, Residence #5	0.30	0.12

slab foundation residences located in the same general area. These results indicate high radon attenuation between soil gas and crawl space air and suggest that pier and beam houses in Houston have a low susceptibility to vapor intrusion impacts. This finding is in contrast to USEPA guidance that suggested that houses with dirt floor crawl spaces have an increased susceptibility to vapor intrusion (USEPA, 2002). This may indicate a difference in susceptibility between houses with above-grade crawl spaces (common along the Gulf Coast) and houses with partially or completely below grade crawl spaces (more common in the northeast, midwest, and northwest).

The presence of elevated radon concentrations below the building foundation at the two Houston slab-on-grade residences and the school further demonstrates the suitability of radon as a tracer over a broad range of geographic areas. The USEPA classifies individual counties in the United States as low, moderate, or high potential for indoor radon problems based on the expected radon emission rates from soils in these areas (USEPA, 1999b). The test locations in Texas (Table 4) and Oklahoma (Table 3) are classified as low radon potential areas while the test location in Utah (Table 3) is classified as moderate radon potential. The soil gas radon levels in all these areas were more than sufficient to reach good measurement precision in short counting times, indicating that accurate soil gas radon measurements should be obtainable in most locations across the United States. We found that the soil gas radon concentrations at our test sites in Texas and Oklahoma (both classified as low radon potential) were higher than at our Utah test site (classified as moderate radon potential). This finding is consistent with the USEPA's warning that their classification scheme is approximate and that local variations in radon potential are significant (USEPA, 1999b).

### Vertical Radon Concentration Profiles

At some sites, the preferred location to measure VOC concentrations in the shallow subsurface is adjacent to rather than below the target building (ITRC, 2007). Collecting soil gas samples adjacent to the building eliminates the need to gain access to the inside of the building and the need to penetrate the building foundation. However, locations adjacent to the building are often exposed to the atmosphere (i.e., not covered by pavement or other low-permeability cover), allowing gas exchange between the soil and atmosphere. As a result of this gas exchange, chemical concentrations in shallow soil gas adjacent to a building may be lower than chemical concentrations in soil gas below the same building. It may be possible to control for this bias by collecting samples at a sufficient depth so that exchange with the atmosphere is negligible. However, the required depth is likely to vary from site to site depending on soil type and other factors.

At the test site in Oklahoma, we measured the vertical radon and VOC concentration profiles in soil gas below and adjacent to the test building in order to determine whether radon could be used to make a site-specific determination of the depth at which gas exchange with the atmosphere does not affect chemical concentrations in soil gas adjacent to the building. The concentrations of radon, TCE, and PCE were measured at one location adjacent to the Oklahoma test building and one location below the test building at depths of 0.5 ft (below building only), 1, 2, 3, and 4 ft in July and December 2006 (Table 6). Adjacent to the building, the radon concentration was low at a depth of 1 ft but higher and relatively stable from 2–4 ft. Radon concentrations in December were approximately 30% higher than the July values. These data, while limited, imply that soil gas values as shallow as 2 ft below ground surface are not significantly affected by dilution from the atmosphere and that seasonal variations in the soil gas concentrations at depths of 2 ft below ground surface or deeper are not large.

Below the building, radon concentrations increased consistently with depth. This variation may be attributable to variations in soil uranium content. More likely, the radon increase may reflect depth-dependent increases in soil moisture, which increases the efficiency of radon emission or decreases in porosity with depth. While the cause for this variation is unclear, it is relevant to note that the radon concentrations adjacent to the building at a depth of 2 ft or greater below ground surface are within a factor

**Table 6a.** Vertical concentration profiles below and adjacent to Oklahoma test building: July 2006\*

Sample depth	Below building			Adjacent to building		
	Radon (pCi/L)	PCE ( $\mu\text{g}/\text{m}^3$ )	TCE ( $\mu\text{g}/\text{m}^3$ )	Radon (pCi/L)	PCE ( $\mu\text{g}/\text{m}^3$ )	TCE ( $\mu\text{g}/\text{m}^3$ )
0.5 ft	542	140	27	—	—	—
1 ft	540	99	5	113	<470	<470
2 ft	741	120	<1.1	594	99	<4.7
3 ft	997	260	30	666	130	<1.2
4 ft	1306	43	13	665	130	<1.2

\*PCE, tetrachloroethene; TCE, trichloroethene.

Table 6b. Vertical concentration profiles below and adjacent to Oklahoma test building: December 2006\*

Sample depth	Below building			Adjacent to building		
	Radon (pCi/L)	PCE ( $\mu\text{g}/\text{m}^3$ )	TCE ( $\mu\text{g}/\text{m}^3$ )	Radon (pCi/L)	PCE ( $\mu\text{g}/\text{m}^3$ )	TCE ( $\mu\text{g}/\text{m}^3$ )
0.5 ft	193	23	1.8	—	—	—
1 ft	391	43	<0.18	363	—	—
2 ft	1068	59	<0.19	744	4.1	<0.17
3 ft	1127	140	12	873	33	<0.17
4 ft	1591	180	16	881	40	<0.18

\*PCE, tetrachloroethene; TCE, trichloroethene.

of two above or below the concentration under the building at the same depth implying that near-building soil gas data from depths of 2 ft or deeper would have given a reasonable estimate of the concentrations under the building.

At the three deeper sample points located adjacent to the building (i.e., 2, 3, and 4 ft), the PCE concentration was within a factor of two above or below the concentration measured directly below the building (i.e., 0.5 ft below ground surface). Thus, at depths where the radon concentration is not depressed, the PCE concentration was representative of that directly below the building. At the 2-ft depth interval, the TCE concentration was similar below and adjacent to the building (i.e., non-detect). However, below the building, TCE is detectable at both shallower and deeper depth intervals. Groundwater is the only known source of subsurface VOCs in the vicinity of this building and the reason for the observed distribution of TCE below the building is not clear.

Although this is a very limited data set, the results suggest that the vertical radon concentration profile adjacent to a building may be useful for identifying the sample depth at which VOC concentrations are most likely to be representative of VOC concentrations below the building. Although this sampling approach would not eliminate the need to characterize spatial variability, an absence of elevated VOC concentrations at multiple locations adjacent to a building could be used to justify a decision not to sample within or below the building if the accompanying radon analyses indicated that the lack of VOCs was not due to mixing of soil gas with the atmosphere. The results obtained suggest that additional study is warranted to validate this potential investigation approach.

## Discussion

Radon measurements provide a simple, yet reliable method to improve our understanding of vapor intrusion at sites with VOCs present in the subsurface. The gas samples can be collected using a variety of storage containers including evacuated counting cells, evacuated canisters or glass vials, and Tedlar bags. These samples can be shipped to an offsite laboratory and can be stored for up to 10 days without significant loss of sample integrity. For indoor air samples, offsite analysis of gas samples provides results similar to those obtained from charcoal canisters commonly used for home radon testing.

Our results along with those of other researchers indicate that radon is a sensitive tracer for the movement of soil gas across a building foundation. Even in low radon concentration areas, typical radon concentrations in soil gas are more than 1,000 times higher than typical ambient radon concentrations (0.2 to 0.7 pCi/L). As a result, for buildings where no soil gas is moving through the building foundations, the measured radon attenuation factor will typically be <0.001 even without correcting for ambient radon. Because very low concentrations of VOCs in soil gas below a building foundation are considered a potential health threat (USEPA, 2002), accurate methods are needed for the site-specific evaluation of soil gas through building foundations. Our results indicate that radon measurements allow for this site-specific evaluation of the soil gas to indoor air attenuation factor and are less prone than some VOCs to confounding by indoor or ambient sources. In addition, vertical profiles of radon concentration in the soil gas may be useful for a variety of other applications such as determining the appropriate sampling depth for VOCs in soil gas adjacent to a building.

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## References

- Arvela, H., A. Boutilainen, I. Makelainen, O. Castren, and Winqvist, K. 1988. Comparison of predicted and measured variations of indoor radon concentration. *Radiation Protection Dosimetry* 24: 231–235.
- DiGiulio, D., Paul, C. Cody, R., et al. 2006. *Assessment of Vapor Intrusion in Homes Near the Raymark Superfund Site Using Basement and Sub-Slab Air Samples*. USEPA Office of Research and Development, EPA/600/R-05/147, Cincinnati, OH, March 2006.
- Interstate Technology & Regulatory Council (ITRC). 2007. *Vapor Intrusion Pathway: A Practical Guideline. VI-1*. Washington, DC: Interstate Technology & Regulatory Council, Vapor Intrusion Team. January 2007. Available at: [www.itrcweb.org](http://www.itrcweb.org) (accessed January 14, 2008).
- Little, J. C., Daisey, J. M., and Nazaroff, W. M. 1992. Transport of subsurface contaminants into buildings: An exposure pathway for volatile chemicals. *Environmental Science and Technology* 26: 2058–2066.
- Lucas, H. F. 1957. Improved low level alpha scintillation counter for radon. *Review of Scientific Instruments* 28: 680–683.

- Mathieu, G. G., Biscaye, P. E., Lupton R. A., and Hammond D. E. 1988. System for measurement of  $^{222}\text{Rn}$  at low levels in natural waters. *Health Physics* 55: 989–992.
- McHugh, T. E., Ahmad, F., and Connor, J. A. 2004. Empirical analysis of groundwater-to-indoor-air exposure pathway: The role of background concentrations in indoor air. *Environmental Forensics* 5: 33–44.
- McHugh, T. E., de Blanc, P. C., and Pokluda, R. J. 2006. Indoor air as a source of VOC contamination in shallow soils below buildings. *Soil & Sediment Contamination* 15: 103–122.
- Mosley, R. B., Cody, R., Willey, D., Digiulio, D., and Lee, A. 2004. Use of radon and per fluorocarbon measurements to project VOC entry rates. In *Proceedings of the USEPA Workshop on Vapor Intrusion* (March 15, 2004, San Diego, CA). Available at: <http://havi.rti.org/resources.cfm?pageID=document> (accessed January 14, 2008).
- Sarmiento, J. L., Hammond, D. E., and Broecker, W. S. 1976. The calculation of the statistical counting error for  $^{222}\text{Rn}$  scintillation counting. *Earth and Planetary Science Letters* 32: 351–356.
- Swedjemark, G. A. 1986. Swedish limitation schemes to decrease radon daughters in indoor air. *Health Physics* 51: 569–578.
- Tanner, A. B. 1980. Radon migration in the ground: A supplementary review. In *Natural Radiation Environment III, Volume 1*, eds., Gesell, T. F., and Lowder, W. M. United States Department of Energy, Technical Information Center, Springfield, VA. 55–56.
- Tillman, F. D., and Weaver, J. W. 2005. *Review of Recent Research on Vapor Intrusion*. USEPA Office of Research and Development, EPA/600/R-05/106, Washington, DC, September 2005.
- USEPA United States Environmental Protection Agency (USEPA). 1992. *Indoor Radon and Radon Decay Product Measurement Device Protocols*. Washington, DC: USEPA, 402-R-92-004, July 1992 (revised).
- USEPA. 1993. *A Physician's Guide — Radon: The Health Threat with a Simple Solution*. USEPA Office of Air and Radiation. EPA-402-K-93-008, Washington, DC, September 1993. Available at: <http://www.epa.gov/radon/pubs/physic.html> (accessed January 14, 2008).
- USEPA. 1999a. *Compendium Method TO-15, Determination of Volatile Organic Compounds (VOCs) in Air Collected in Specially-Prepared Canisters and Analyzed by Gas Chromatography/Mass Spectrometry (GC/MS)*. USEPA. Cincinnati, OH, EPA/625/R-96/010b, January 1999.
- USEPA. 1999b. *Map of Radon Zones*. Cincinnati, OH: USEPA. EPA-402-R-93-071, August 1999.
- USEPA. 2002. *OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)*. USEPA. Washington, DC, November 2002. Available at: <http://www.epa.gov/epaoswer/hazwaste/ca/eis/vapor.htm> (accessed January 14, 2008).