Use of Radon to Determine Attenuation between Subslab and Indoor Air for Vapor Intrusion Evaluation at Military Housing Units at Fort Wainwright, Alaska

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An indoor air investigation has been conducted in support of a risk assessment for the Remedial Investigation at a 50-acre future housing site on Fort Wainwright, Alaska. A phased vapor intrusion (VI) evaluation approach using multiple lines of evidence, consistent with the DoD (2009), ADEC (2009), and USEPA (2002) guidance was followed. A critical component of the risk characterization was the evaluation of a VI pathway using subslab soil gas collected from each of the 110 similarly-constructed, unoccupied living units. Paired subslab/indoor VOC samples in a subset of the units, along with outdoor ambient air VOC samples, were collected to evaluate site-specific attenuation factors that could be applied sitewide to the subslab soil gas results. However, due to the serious limitations inherent in identifying a site-specific attenuation factor using volatile organic compounds (VOCs) (for example, VOCs either not detected indoors, detected at levels consistent with background, and/or detected at levels above subslab levels), an alternate approach was selected using naturally-occurring radon as a reasonable surrogate to overcome the limitations with VOCs. The limitations inherent in directly using VOCs were construed to be largely the result of the low source strength (low VOC levels in subslab soil gas) at the site. The calculated radon attenuation factors were very consistent among the 19 housing units tested. Moreover, the degree of attenuation was relatively consistent temporally, with January representing slightly less attenuation than during May and August. Because of the observed spatial and temporal consistency and the relatively uniform building construction design across the site, radon provided a good surrogate for estimation of a site-specific attenuation factor, very consistent with the attenuation factors reported in the USEPA national database.

Introduction

Fort Wainwright is within the Fairbanks North Star Borough (FNSB) in central Alaska. The Taku Gardens Family Housing development at Fort Wainwright covers 54 acres and includes 110 new housing units (in 55 buildings). The buildings are intended for use as family housing for Fort Wainwright military personnel and their families but are currently unoccupied.

Based on review of historical photographs (dating from 1947 to the present), the 1958 Fort Wainwright "Master Plans," past geographical surveys, and military operations concurrent with similar missions conducted at other locations, it was determined that the housing development area had a history of mixed uses, including salvage/reclamation yard activities, debris disposal, garden plots, barracks and company headquarters, communication and radar systems, possible ammunition storage, and possible firefighter training. The area was selected for military family housing in 2002 and 2003. Initial investigations intended to support construction activities included geophysical, geotechnical, and some subsurface-soil-sampling. During these early investigations, the first indications of buried debris, munitions-related items, and contaminated soils were identified at the site. As a result, a remedial investigation (RI) was initiated in 2007, including a human health risk assessment.

Vapor intrusion (VI) investigation activities were conducted as part of the RI for the site to determine whether there was a potential pathway of exposure to future residents by inhalation of volatile organic compounds (VOCs) migrating to indoor air. The goal of the VI investigations was to develop informed and reliable estimates of the potential for risk to future military occupants of the housing units, to support defensible risk management decisions by the Army, USEPA, and ADEC. The approach for evaluating the VI pathway was consistent with the tiered process recommended in USEPA Vapor Intrusion Guidance[1] and ADEC Draft VI Guidance[2].

The preliminary results of the evaluation of attenuation factors (AFs) for ten duplex units indicated that chemical-specific attenuation factors could not be derived for all of the VOCs detected, due to the limitations inherent in the results (for example, VOCs not detected indoor, detected at levels consistent with background, and/or detected at levels above subslab levels). This was construed to be largely the result of the low source strength (concentrations in subslab soil gas) at the future housing site. Therefore, more careful assessment of a site-specific attenuation factor was merited. Due to the limitations inherent with the use of VOC data to directly measure site-specific attenuation, an alternative approach using radon as a tracer was selected. Radon is naturally present in soil gas and ambient air, is not likely to originate from subsurface contamination, and 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. Moreover, the fact that all buildings were constructed using the same styles, at the same time, using the same construction materials, and that no occupants have yet taken residence offers circumstances that are somewhat unique for vapor intrusion investigations.

Deriving a Site-Specific Attenuation Factor for Subslab to Indoor Air

Identifying the rate of attenuation of soil gas to indoor air is a critical step in estimating indoor air concentrations from levels detected in subslab soil gas. The AF is computed as the VOC indoor air concentration divided by the corresponding concentration in subslab soil gas:

$$AF = \frac{C_{Indoor}}{C_{Subslab}}$$

Where:

AF = attenuation factor (unitless)
C_{Indoor} = indoor air concentration (micrograms per cubic meter [$\mu g/m^3$])
$C_{Subslab}$ = subslab soil gas concentration ($\mu g/m^3$)

The smaller the AF, the more attenuation is occurring. In a practical sense, the AF is the measure of how soil and building properties limit the intrusion of organic vapors as they migrate into a structure. The objective in estimating an empirical AF for VI is to minimize bias resulting from aboveground background sources of VOCs and low-source strengths[3]. An estimate can be developed by applying appropriate VOC data filters, using tracer compounds (e.g., radon), or both.

For the Taku Gardens evaluation, a site-specific AF was derived as an alternative to using modeling approaches (for example, the Johnson and Ettinger model), which incorporate default and somewhat conservative assumptions and methods. Moreover, these models and default AFs generally require that the soil column properties within the zone of influence of the building (e.g., porosities, bulk density, etc.) be homogeneous, and that the soil be isotropic with respect to vapor permeability. Given the possibility that these conditions may not exist beneath the buildings at the Taku Gardens site because of potential buried debris and disturbances during construction, derivation of a site-specific factor was considered to be justified. The process of developing this site-specific AF for the housing units is described below.

Evaluation of VOCs for Derivation of a Site-Specific Attenuation Factor

Indoor air and subslab soil gas VOC samples were collected in December 2008 from 10 representative living units to provide paired indoor air–subslab sampling under the most realistic living conditions. The temperatures of the units were documented to be generally around 68 degrees Fahrenheit (°F) with ventilation systems running at the time of sampling. The purpose of this sampling was specifically to determine whether VOCs could be suitable for derivation of site-specific AFs.

To identify any confounding influences from ambient background (offsite) sources of VOCs, background samples were also collected on the east and west property fence lines in December 2008 and August 2009. Outdoor air enters a structure typically through infiltration, natural ventilation, and mechanical ventilation. Studies have shown that common background pollutants are two to five times higher inside a structure, compared to levels in the ambient air (EPA,[4,5] New Jersey Department of Environmental Protection,[6] Girman[7]). For evaluating confounding influences from ambient background, the assessment considered a conservative level of two times the average background VOC concentration as a level in indoor air potentially contributed by ambient sources, and not from subslab sources. This value was a primary data-filtering criterion for elimination of specific VOCs as candidates for deriving a site-specific AF. Use of this approach is consistent with the EPA[8] recommendation to apply filtering steps before calculating empirical AFs.

The results from the paired indoor air/subslab sampling indicated that 29 VOCs were detected. Listed in order of hierarchy, the following three primary criteria were used to eliminate specific chemicals from use in deriving a site-specific AF:

1. The measured indoor concentration was greater than or equal to the subslab concentration, indicating that the chemical is likely contributed from an indoor or ambient background source.
2. The indoor concentration was less than twofold the average background level, suggesting that the chemical is likely from an ambient background source.
3. The indoor concentration was not detected, and VI was not measurable.

The results of the paired indoor air/subslab sampling indicated that chemical-specific AFs could not be derived for any of the VOCs detected because of the limitations inherent in the results (that is, failure to meet the three criteria above). This finding was attributed largely to the low source strength (concentrations in subslab soil gas) at the future housing site. Of 290 computed ratios for indoor-to-subslab concentrations, only two VOCs had enough "separation: between the detected indoor level and the detected subslab level to provide even a rough estimation of an AF:

> Chloroform in Unit 42L
> (indoor/subslab = 0.12J/190 micrograms per liter (µg/L) = 0.00063)
>
> Tetrachloroethene in Unit 34R
> (indoor/subslab = 0.58/110 µg/L = 0.0053)

Even these values, however, were influenced by indoor levels consistent with background levels, and the total degree of attenuation may not have been fully evident.

It has been documented by EPA[3,8] that the AF for VOCs is most reliable when the source strength is considerably higher (e.g., about 10-fold or more) than ambient background levels, thereby minimizing the confounding influences of background or the truncation of indoor levels because of detection limits. The VOC levels found in subslab soil gas at the future housing site appear to be too low to provide a defensible measure of attenuation. To provide a comparative perspective, significant VI sites being investigated by ADEC in Fairbanks, as part of its Contaminated Sites program, have reported subslab VOC concentrations from two to four orders of magnitude higher than the highest levels observed at the future housing site.[9]

Evaluation of Radon for Deriving a Site-Specific Attenuation Factor

Because of the limitations inherent with the use of VOC data to directly measure site-specific attenuation at the future housing site, an alternative approach using radon as a tracer was selected. The measurement of radon concentrations in soil gas and indoor air is a useful tool for evaluating sites with potential VOC VI impacts because it allows determination of soil gas transport through the building foundation. The advantages of using radon as a surrogate tracer include the following:

- Radon is naturally generated in the vadose zone, is present in soil gas and ambient air, and is not likely to originate from subsurface contamination.
- 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 of VOCs (McHugh et al.[10]) because radon is generally not found in building materials.
- Unlike some VOCs, radon measurements are not prone to confounding by ambient sources.
- Radon concentrations in soil gas are generally more than 100-fold higher than in outdoor air. EPA has classified Fairbanks North Star Borough, Alaska, as a Zone 2 county (of three zone categories) with moderate potential for radon occurrence.
- Radon is considered a conservative tracer because of its inert nature and lack of chemical interaction with soil, as would be expected for organic VOCs.
- Radon is easily sampled and analyses are relatively inexpensive.

Use of radon measurements to derive the site-specific AF of the soil gas to indoor air is consistent with recommendations in vapor intrusion guidance. Section D.11.2, "Determination of Slab-Specific Attenuation Factor Using Tracers," in *Vapor Intrusion Pathway: A Practical Guide*, by the Interstate Technology & Regulatory Council[11] states the following:

> Measurement of a conservative tracer inside the structure and in the subslab soil gas can enable calculation of a site-specific attenuation factor. The calculated attenuation factor can then be used to estimate the indoor air concentration of other COCs by multiplying the measured subslab soil gas concentration by the attenuation factor for the tracer (or "marker compound"). This method assumes that all subslab vapor phase contaminants are entering the building at equal rates, a relatively safe assumption for most situations. *Naturally occurring radon is the most commonly used conservative tracer* [emphasis added].

The Department of Defense (DOD) *Vapor Intrusion Handbook*[12] also supports the use of radon as a tracer:

> *Marker Chemicals or Tracers:* At some sites with sufficiently large datasets, it may be possible to use marker chemicals or tracers (e.g., 1,1-dichlroethylene [1,1-DCE], *radon*) to help filter out data that are not likely associated with VI. Tracers are VOCs that are detectable in VI samples, but rare in "background" indoor air. 1,1-DCE is one such constituent and was used to distinguish background sources from VI sources at the Colorado Redfield site (Kurtz and Folkes, 2002). *Tracers also can be used to estimate a site-specific sub-slab to indoor air attenuation factor (i.e., $C_{indoor}/C_{sub\text{-}slab}$), which can be used to compare with attenuation factors of target VOCs.* In this case, one should work

> with measured tracer indoor air concentrations that are greater than 10× the reasonably expected background concentrations or analytical detection limits [(emphasis added].

McHugh et al.[10] reported that attenuation values derived with the use of radon were consistent with values derived with the use of chlorinated solvents.

Radon Sampling and Analysis

In March 2009, August 2009, and January 2010, subslab soil gas and indoor air samples were collected for radon analysis at five of the Taku Gardens housing units. The units represented different home styles at the development, but all had approximately the same square footage. During the January 2010 sampling, five additional units (those with the highest ADEC target level exceedances for VOCs from the December 2008 and August 2009 events) were also sampled for radon in subslab soil gas and indoor air. To strengthen the statistical power of the radon data, each of the 10 adjoining units was also sampled in January 2010, resulting in a total of paired subslab and indoor air samples from 19 units.

The heating and ventilation systems in each unit were set to simulate typical living conditions; indoor temperatures were generally around 68°F at the time of sampling. Subslab samples were taken from the same permanent probes installed in the garages of the housing units that were used to collect subslab soil gas samples for VOC analysis during the RI. Indoor air samples were taken from a central location inside each home. To provide some perspective on radon levels in ambient outdoor air, two outdoor samples were taken from the same locations from which background VOC samples had been collected during the RI. All samples were taken using a Tedlar bag placed in an airtight box that was evacuated by use of a sampling pump during an approximate 5-minute period. The vacuum pump created a negative pressure within the box, which allowed the bag to fill with sample. Using this sampling technique, the air sample never passed through a pump, thus eliminating the chance of cross-contamination between samples.

The samples were submitted to the laboratory at the Department of Earth Sciences, University of Southern California, Los Angeles, California, for analysis. Radon-222 was analyzed by using alpha scintillation counting in accordance with established EPA protocols.[13] A sample aliquot was drawn from the Tedlar bag, passed through a drying column of calcium sulfate, and injected into a Lucas style counting cell, coated with a zinc sulfide phosphor. Activity in the cell was determined by using an Applied Techniques radon counter. The cell efficiency was determined based on radon extracted from standards made from calibrated 226Ra solutions, with activities traceable to National Technical Information Service standards. Corrections were made for cell backgrounds, decay from sampling to analysis, and changes in atmospheric pressure from the site to the laboratory. Additional details can be found in McHugh et al.[10]

Radon Results

The radon concentrations (in picocuries per liter) found in indoor air were divided by the concentrations in subslab air to determine the AFs. Results from the analyses of radon attenuation were assessed for temporal (Table 1) and spatial (Table 2) variability. For radon analyses from March 2009, August 2009, and January 2010, the average AFs were 0.0013, 0.0011, and 0.0018, respectively. These results indicate that the degree of attenuation is

Table 1
Temporal Variability of Radon Attenuation from Subslab Soil Gas to Indoor Air
Former Communications Site, Fort Wainwright, Alaska

	Subslab			Indoor Air			Attenuation Factor			Annual
Unit	Mar-09	Aug-09	Jan-10	Mar-09	Aug-09	Jan-10	Mar-09	Aug-09	Jan-10	Average
02L	362	437	383	0.52	1.07	0.76	0.0014	0.0024	0.0020	0.0020
25L	355	369	351	0.52	0.37	0.54	0.0015	0.0010	0.0015	0.0013
34L	435	472	410	0.35	0.26	1.24	0.0008	0.0006	0.0030	0.0015
42L	414	390	442	0.44	0.41	0.77	0.0011	0.0010	0.0017	0.0013
63L	579	614	525	0.95	0.43	0.33	0.0016	0.0007	0.0006	0.0010

Min =	0.0008	0.0006	0.0006	0.0010
Max =	0.0016	0.0024	0.0030	0.0020
Mean =	0.0013	0.0011	0.0018	0.0014

Table 2

Spatial Variability of Radon Attenuation from Subslab Soil Gas to Indoor Air

Former Communications Site, Fort Wainwright, Alaska

Unit	Subslab Jan-10	Indoor Air Jan-10	Attenuation Factor Jan-10
02L	383	0.76	0.0020
02R	180	0.54	0.0034
08L	420	1.15	0.0027
08R	384	0.89	0.0023
12L	418	0.90	0.0022
12R	361	0.80	0.0022
16L	311	0.65	0.0021
16R	339	1.00	0.0029
20L	446	0.55	0.0012
20R	369	0.57	0.0015
25L	351	0.54	0.0015
25R	344	0.56	0.0016
34L	417	1.24	0.0030
34R	404	0.70	0.0017
42L	442	0.77	0.0017
47L	369	0.57	0.0015
47R	366	1.13	0.0031
63L	525	0.33	0.0006
63R	639	0.66	0.0010

Min =	0.0006
Max =	0.0034
Mean =	0.0020

relatively consistent temporally, with January representing slightly less attenuation than during May and August.

Results of the January 2010 sampling at 19 units (Table 2) indicate AFs ranged from 0.0006 to 0.0034, with an average of 0.0020. Recognizing the very similar construction design used for all units at the future housing site, this relatively small range is not surprising, and likely reflects both spatial and analytical variability. To derive an AF for use in the VI evaluation, the 95% upper confidence limit (UCL) of the values from these 19 units was computed by using the EPA online ProUCL calculation tool, Version 4.00.04,[14] in accordance with risk assessment guidance (EPA 1989). For the five units that were analyzed during three sampling events, the annual average AF was used as a proxy for that unit during the computation of the 95% UCL. The 95% UCL using this approach was computed to be 0.0022, and this was the value used for estimation of vapor intrusion risks for the RI.

It should be noted that the computed AFs were not corrected for ambient radon concentrations (that is, ambient radon was not subtracted from the indoor concentration). As a result, these radon AFs may be biased high and therefore under-represent the true attenuation at the future housing site. The approach was selected to provide a health-conservative estimate of actual attenuation.

The derived AF of 0.0022 is consistent with values reported by some regulatory agencies and other literature sources, including AFs reported in the EPA Vapor Intrusion Database (EPA[3] updated in 2010). The California Environmental Protection Agency in its *Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air*[15] has set a default attenuation factor of 0.002 for existing residential buildings with slab-on-grade construction. Further, McHugh et al.[10] used this radon attenuation method to measure subslab-to-indoor AFs in six buildings, with the resulting values ranging from 0.0002 to 0.006.

The following findings and conditions support the determination that the AF of 0.0022 is appropriate for use in estimating indoor air concentrations from measured subslab VOC concentrations at the future housing site:

- The scientific foundation for use of radon as a surrogate for VI
- The observed spatial and temporal stability of vadose zone radon measured at the future housing site
- Consistency with reported literature and regulatory sources

Lines of Evidence Supporting Conclusions about the Vapor Intrusion Pathway

The attribution of chemicals in indoor air to VI can be a relatively complex and difficult task. Regulatory guidance recommends that the VI pathway be evaluated by using multiple lines of evidence to develop decisions that are based on professional judgment.[1,2,11,12]. As outlined in the ITRC *Vapor Intrusion Pathway: A Practical Guideline*,[11] the following lines of evidence are examples of the types of data that should be considered when assessing the VI pathway:

- Soil gas spatial concentrations
- Groundwater spatial data
- Background, including internal and external sources
- Building construction conditions
- Indoor air data
- Concurrent outdoor air data
- Constituent ratios

Each of these lines of evidence, as well as others, was evaluated by considering the entire data set generated during the RI at the future housing site. The available lines of evidence are summarized as follows:

- Soil-gas concentrations of chlorinated VOCs do not reflect the presence of strong spatial concentration gradients that would indicate that point source releases have caused noticeable hotspots of soil vapor contamination. The maximum VOC concentrations seen in vadose zone soil gas that was collected at 6 feet below ground surface are in the same range as the maximum VOC levels seen in subslab soil.

- Soil-gas concentrations of chlorinated VOCs do not correlate spatially with VOCs detected in soil at the future housing site. The locations where surface and subsurface soil VOC concentrations were highest were not found to have an obvious spatial correspondence with the distribution of detections in soil gas. This lack of correspondence suggests that higher concentration areas in subsurface soil are not spatially connected with localized VI, and that VI cannot be connected to a specific source or location in soil. It is possible that current VOC patterns in soil gas reflect sources already removed during excavations at the site.

- Soil-gas concentrations of chlorinated VOCs do not correlate spatially with VOCs detected in shallow groundwater at the future housing site. The locations where groundwater VOC concentrations were highest were not found to have an obvious spatial correspondence with the distribution of detections in soil gas. This lack of correspondence suggests that higher concentration areas in shallow groundwater are not spatially connected with localized VI, and that VI cannot be connected to a groundwater source.

- Indoor soil-gas concentrations do not appear to conclusively originate from subslab sources. In a representative set of 10 housing units, the measured indoor concentrations of VOCs were either (1) at levels exceeding subslab levels, (2) at levels consistent with levels seen in ambient air, or (3) not detected indoors.

- The consistent building construction design, size, and history of the housing units at the site allow for sitewide generalization to a greater degree than would be apparent at other more heterogeneous sites. The conditions that all buildings were constructed using the same styles, at the same time, using the same construction materials, and that no occupants have yet taken residence offer circumstances that are somewhat unique for VI investigations. Therefore, representative AFs measured at a subset of 19 of the 110 living units are assumed to be applicable to all of the units for assessment of inhalation exposure and risk.

- Concentration ratios of VOCs in subslab soil gas are not consistent with ratios seen for VOCs in indoor air. If indoor air is dominated by subsurface VI, the VOC concentration ratios in indoor air would be expected to be roughly similar to those seen in subslab soil gas. In a representative set of 10 housing units, however, the ratios among VOC concentrations in subslab soil gas are not consistent with the ratios among VOC concentrations in indoor air for any of the 29 detected VOCs or any of the units. For example, the PCE:TCE concentration ratio for subslab soil gas at unit 34R is 110/0.028J $\mu g/m^3$, or 3,929, whereas the PCE:TCE ratio for indoor air at the same unit is 0.58/0.035, or 17. The inconsistency of the ratios within subslab in comparison to those ratios within indoor samples suggests that indoor air concentrations are not due to vapor intrusion.

- Sampling data from all 110 living units provide for a robust data set and complete site coverage. By sampling all of the living units at the future housing site, subslab VOC data did not need to be interpolated from building to building or from unit to unit. Also, each of the 55 buildings was sampled during seasonal extremes (December and August). These results provide valuable detail about the relative degree of variability in subslab soil gas and support the conclusion about the absence of vapor hotspots across the future housing site.

- Risk estimates do not exceed EPA or ADEC regulatory thresholds for subslab VOC concentrations. All indoor concentrations were conservatively assumed to originate from subsurface contamination. Even without subtracting known background concentrations of VOCs, unacceptable risks were not observed during the RI when a site-specific AF derived with the use of radon was included.

Interpretation of the available monitoring data generated during the RI indicated that all lines of evidence corroborate to support the conclusion that the VI pathway does not represent unacceptable risk at the future housing site. When considering the collective weight of all the lines of evidence listed above, ample evidence exists to support this conclusion for reasonably anticipated future residents of the Taku Gardens housing development.

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Key Words

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