TECHNICAL BASIS FOR THE USE OF INDOOR RADON MEASUREMENTS FOR CHEMICAL VAPOR INTRUSION CONCERNS

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Abstract

Since the presentation of *Chemical Vapor Intrusion 'A Nucleus for Cultural Change?'* (Schuver, 2012) and *Indoor Radon as an Option for On-going Screening/Monitoring of Chemical Vapor Intrusion* (Schuver, 2014), the USEPA's Resource Conservation and Recovery Act (RCRA) corrective action program and Office of Research and Development (ORD) has been exploring the measurement of indoor radon (Rn) as an indicator for subsurface chemical vapors. The specific uses of Rn measurements being pursued were described in *Indicators of VI: Evidence-based Hypotheses for Supplemental Tools for Assessing & Managing Low/Episodic Chlorinated-VI* (Schuver, 2016). This presentation/paper will summarize the technical basis and further testing of these hypotheses for advancements in guidance implementing the use of Rn as a tool for addressing chemical vapor intrusion problems. In summary, Rn is proposed for classifying buildings for susceptibility to intrusion, and forming a 'complete' exposure pathway, or not. Rn can also focus chemical assessments on which buildings and times for Reasonable Maximum Exposure conditions and allows Long-Term verification for being 'Soil Gas Safe.'

Introduction

We have made significant progress since the turn of the century in getting many of the more continuously-unacceptable chlorinated-chemical Vapor Intrusion (CVI) exposures 'under control' at known sites where any indoor air sample can identify a problem. However, two questions remain as major barriers to developing a more confident and effective elimination of all CVI concerns at the majority of sites: Where to sample? and When to sample?

In particular, concerns can remain at the more common, but less clear, 'grey-zone' sites and buildings where what-is-typically-considered 'low-to-moderate' CVI potential conditions can still cause episodically-unacceptable exposure periods, particularly under Reasonable Maximum Exposure (RME) conditions. RME conditions are the required criteria for decision making under the USEPA VI Guide (EPA, 2015a; RME "A semi-quantitative term, referring to the lower portion of the high end of the exposure distribution; conceptually, above the 90th percentile exposure but less than the 98th percentile exposure"). RME conditions can be of particular concern when considering possible developmental health effects such as those associated with trichloroethylene (TCE) exposures to pregnant women, where short-term (e.g., some few days) exposures can be a concern. The two major remaining questions to assess a CVI site under reasonably expected/current conditions, using a limited number of indoor air samples from a subset of buildings to represent CVI RME in all un-sampled buildings and times (i.e., a site-wide RME condition), are thus, first and most importantly:

1) **Where** (which buildings) **to Sample?**

Decades of indoor air measurements for the intrusion of radon (Rn) gas, in buildings overlying generally homogenous Rn source levels, has shown that it is highly building-specific. The Rn gas intrusion pathway is analogous to CVI in many ways, e.g., within categories-of-variables (#1 and #2) as shown in Figure (1) below, but also different in important ways. The Rn intrusion pathway is both shorter (i.e., from only a couple of meters, due to travel times and Rn's relatively 'short' 3.8 day half-life) and simpler, than the typical CVI pathway which is also influenced by two (deeper) additional categories-of-variables (#3 and #4) in Figure (1) below. Nevertheless, after more than three decades of observations and measurements, Rn intrusion has not been found to be practically predictable, even for 70-yr-lifetime-average exposures, i.e., without sampling all individual buildings and across time. It is unpredictable in two regards: 1) Spatially, i.e., the identification of individual buildings and zones within buildings with elevated Rn from among those in broad geographical areas of similar radon potential is not predictable; and 2) Temporally, i.e., the level of Rn at any specific time within a building is not practically predictable, but is observable. Temporal variability is not practically predictable because complex models are needed including a large number of input variables taken often right up to the time of the prediction and yet they provide only approximate estimates of the indoor Rn levels measured.

Four Major Categories-of-Variables for CVI	**Radon (Rn)**	**Chlorinated-chemical Vapors**
1) VI-Driving Forces (atmospheric - temperature, pressure, winds, etc.)	~Same (near structure) [Primary initial-driver of Advection for soil gas Intrusion into buildings]	~Same (near structure) [Primary initial-driver of Advection for soil gas Intrusion into buildings] (Note, at depth, Diffusion driven by chemical concen-tration gradient is the driving force for deep CV migration)
2) Building Factors (including adjacent soil/materials/structures/piping within the building's advective sweeping/capture zone)	~Same [Primary limitation on the amount of intrusion/retention (i.e., attenuation of concen-trations)]	~Same [Primary limitation on the amount of intrusion/retention (i.e., attenuation of concen-trations)]
3) Deep Subsurface Migration / Attenuation	Not important for Rn as little from depths ~>2 m gets indoors in most geologies, as slow travel time and short	Variable w/ ground-water table depth(s), geologies, vadose zone soil moisture

	3.8 day half-life limits amount from deeper depths	content, etc.
Vapor adsorption to media	Inert ~ no chemical interaction	Variable (across space and time) interacting with media, e.g., % carbon, etc.
Vapor depletion/decay w/ time	Constant (3.8 day half-life)	Variable but gen. slow (>180 day) for highly chlorinated ethenes and ethanes
Vapor 'capping'/'build-up' (under foundation/slab)	Not observed or expected (to be significant, due to short half-life)	Expected from 3D models and Observed
'atypical' preferential pathways	Not a differential w/ or w/o - If 'pipes'/structures are sufficiently open to near-building soil gas entry (e.g., travel time to indoor air is <1 week)	Variable difference – If, e.g., far distant CV source released/leaked high concentrations into sewer/piping directly connected to indoor air (but is not open to subsurface near-building)
4) Source of vapors – Location, across Space and Time	Non-mobile mineral in-situ over geologic time periods (w/o human excavations)	Free-phase Liquid/dissolved organic/gas or Vapor; Mobile plumes [with concentration pulses] variable across, x, y, z (w/ time)
Vapor generation, Amounts across Time	Constant - atomic decay of radium mineral	Variable (w/ release timing, groundwater conc. pulses, rising/falling water table, interacting w/ grain size, capillary fringe height, etc.)

Figure (1). Table comparing similarities and differences between Radon and Chemical Vapor Intrusion across the Four Major Categories-of-Variables for CVI.

For chemical vapor intrusion (CVI), currently only indoor air concentrations can integrate all of the factors influencing CVI levels at specific locations and times. Unfortunately, these indoor chemical measurements are quite disruptive and expensive as well as also being subject to interference from confounding indoor and outdoor 'background' sources, which can add significant costs to each building sampled. However, indoor Rn concentrations can reflect and integrate all of the variable factors influencing the intrusion of the near-building soil gas, i.e., soil gas subject to the advective sweeping within the building's 'capture zone.' This soil gas typically includes measureable levels of Rn and may also include chlorinated-chemical vapors (CV). Fortunately, the measurement of indoor Rn has been made both practical and affordable, i.e., even continuously and in multiple buildings.

Radon is widely distributed and often in readily measureable levels in soil gas and indoor Rn concentrations can be useful as a tracer of soil gas intrusion (e.g., where indoor Rn levels are elevated relative to outdoors). The measurement of indoor Rn levels in all buildings overlying CVI sources could be used to prioritize and classify the susceptibility of (many) individual buildings to the intrusion of nearby soil gases (i.e., wherever adequate levels of Rn are present in soil gas). If the soil gas near these buildings has also been documented to contain CV, the combined confirmation of the intrusion of near-building soil gas (e.g., elevated indoor Rn levels), and having CV in the same near-building soil gas, could be used to qualitatively categorize/indicate these buildings, as having a likely 'complete' CVI pathway (i.e., some amount of intruded CV exposure). These buildings could then be prioritized for indoor CV sampling, since they have now been shown to be in a subset of buildings with documented soil gas intrusion and thus capable of possibly hosting the site's RME conditions. Note that "nearby" soil gas, typically considered to be within a few meters of a building, can include some gas from a longer physical distance away if 'atypical' preferential flow pathways for soil gases may be present. In that scenario, indoor Rn could still be a useful tracer of soil gas movement via these structures (e.g., Barker, 1999; AARST, 2012), i.e., when flow brings the soil gas into the building within approximately one-week's travel time.

If the subset of buildings found to be capable of hosting a site's RME concentrations are still considered too numerous to conduct CV indoor sampling from all of them, it may be possible to further prioritize them by documenting/quantifying the average levels of Rn in the general area's soil gas, so it can be compared the indoor levels, and a rough building-specific estimate of the average indoor to nearby soil gas Rn attenuation factor (Rn_{in}/Rn_{sg}) be derived. It would not be appropriate to use such a roughly estimated Rn attenuation factor, along with a few soil gas CV grab samples, to directly-quantitatively estimate indoor CV levels for risk-based decision-making, given the uncertainty and likely CV source variability and other CV-specific variables. However, it may be appropriate to rank-order the derived building-specific Rn-entry/retention (attenuation) characteristics, if given a demonstration of Rn's generally equivalent source levels across the buildings being considered for CV sampling. Thus, it appears conceptually possible that building-specific Rn intrusion-attenuation characteristics could be considered semi-quantitatively (i.e., rank-order), as needed, for further prioritization to a smaller subset of buildings for indoor CV sampling. The validity of this concept for using indoor Rn to rank-order the buildings that can represent the site's RME (spatially) should be tested appropriately, and compared to other available approaches for using measured evidence to select a subset of site-RME (spatially) representative buildings.

In summary, regarding 'Where to Sample", conceptually and empirically based on both Rn and chemical data (e.g., Lutes, 2010), Rn could be considered a useful evidential-indicator of individual building or smaller interior-space's qualitative, and possibly rank-ordered, susceptibility to the intrusion of near building soil gas, i.e., soil gas which likely includes sufficiently-elevated levels of Rn and may include CV. Once an empirical measured-evidence-based process for selecting an appropriate and practical subset of buildings for indoor CV sampling has been used, and a subset of site-RME-capable/representative buildings identified, it would then be appropriate to consider "When to Sample" CV in indoor air of the selected/prioritized buildings to best represent site-wide RME levels across time.

2) **When to Sample?**

As part of a generic-Conceptual Site Model (CSM) for soil gas intrusion, both Rn and CV can be components of near-building soil gas. Thus, both can share the influence of the two closest and most important categories-of-variables primarily determining intrusion levels and times; i.e., VI-driving forces and Building factors (#1 and #2, respectively, in Figure (1)), which govern the entry and retention/dilution of near-building soil gas. Furthermore, Rn and CV have been found (in both of the data-rich simultaneous Rn and CV studies currently available to us) to have generally visibly correlated (e.g., Holton, 2012) and, where conducted, strong (e.g., ~99% in the most recent data sets) statistical correlation in the *direction* of concentration changes (increasing/decreasing) together across time (EPA, 2015b). This is consistent with Rn and CV being components of the same near-building soil gas, and intruding into indoor air similarly and together across time. Thus, conceptually and empirically (from the data-rich studies available), Rn could be considered a useful surrogate for the temporal behavior of CV in near-building soil gas; with some qualifications for the differences in the additional variability in concentrations seen for CVI.

The evidence from both of the data-rich simultaneous Rn and CV studies (SERDP-ESCTP, 2016; EPA, 2015b), have shown the range of variability for CV indoor levels is somewhat (perhaps one to two orders-of-magnitude) greater than for Rn. This difference may commonly be due to the additional variability from deeper zones which only influence CV intrusion levels; i.e., changing CVI-Source levels and varying Deep/diffusive-migration/attenuation. This difference in the range of variability may also result from the 'capping' effect on sub-slab concentrations of long-lived CVs that would not 'build-up' to the same degree for Rn due to its much shorter half-life. Finally, this difference in variability of concentrations may be a result of the presence of 'atypical' preferential pathways, that may contain or have direct access to high CV source levels, but are not connected to as strong a source of radon, at least within a about week's travel time/distance (i.e., less than a few Rn half-lives). The EPA's statistical analysis of the ~80 unique variables studied as possible predictors of indoor CV levels found that indoor Rn levels had the highest association, generally predicting from 40-60% of the *magnitude* of indoor CV concentration changes, in the most recent (28 week) data set (that we note, did not include a summer, EPA, 2015b).

Despite the observed greater variation in CV concentrations, on-going high-frequency or essentially 'continuous' measurements of indoor Rn could be used to directly show the variability in intrusion levels of nearby-soil gas over time, and given the strong statistical correlation (e.g., ~99%) in the *direction* of concentration changes, can also indicate a similar (e.g., increasing/decreasing) intrusion behavior for CV that is present in the same near-building soil gas. Furthermore, because high-frequency indoor Rn data can be affordably collected, adequate indoor Rn data could be collected to allow for the reliable statistical quantification of the building-specific RME for Rn intrusion from all those buildings selected as being capable of hosting, or more likely representing, site-wide RME conditions. Therefore, because Rn and CV have been found to be strongly correlated in the *direction* of concentrations changes (increasing/decreasing) together across time, and that the variability of *magnitude* of CV levels is generally found to range more widely than for Rn, it could be expected that a period of significantly elevated levels for Rn (e.g., a statistically verified RME_{Rn} period) could also be an RME time-period for CVI (RME_{CVI}). The validity of this temporal-RME expectation/correlation between Rn and CV should be tested appropriately, and compared to other available approaches for using measured evidence to quantitatively select a subset of more likely RME representative times for indoor CV sampling.

Overall Summary and Conclusions

Current conceptual understanding and existing evidence for the complexity and variability of CVI suggests an evidently valid (based on the data-rich Rn-CVI studies available) and practical approach for defining and sampling for site-wide RME conditions, could begin by:

- Assessing all buildings overlying a CVI-source area using indoor air measurements, e.g., most practicably with a tracer/indicator/surrogate, such as Rn, and then using:

- a subset of the buildings overlying a CVI-source with measured evidence (e.g., via soil gas tracer) of them being susceptible to soil gas intrusion and thus capable of possibly hosting the site's spatial RME conditions, along with

- a well-established statistical description of these building's temporal RME conditions for soil gas intrusion, based on long-term on-going indoor monitoring (e.g., using a tracer of soil gas intrusion), and

- then collecting indoor CV samples from those buildings during a period of time that can be statistically confirmed as meeting their RME criteria for soil gas intrusion (e.g., via the simultaneous measurement of a tracer of soil gas intrusion);

This approach could increase the likelihood of collecting CVI samples representing RME_{CVI} conditions in both a spatial and temporal sense. That is, these CV samples would then be more likely to represent both the RME of the sampled subset of buildings as well as other un-sampled (for CV) building's and times. Thus, using data-rich indoor air measurements of soil gas intrusion tracer/indicator/surrogates, such as Rn, the site-wide RME_{CVI} conditions could be defined and cost-effectively sampled across both space and time, with a documentable degree of confidence unattainable by other methods (practical at this time).

Implications

Given adequate levels of Rn in soil gas to be an effective tracer/indicator/surrogate for CVI; And if all of the indoor CV samples collected from Rn-indicated RME intrusive capable/prioritized buildings showed CV risks below or at the bottom end of the risk management range, additional sampling of additional structures might then be foregone (under the current/near-term expected conditions). If, however, some of these selected/prioritized indoor CV samples showed risks above or at the upper end of the risk management range then sampling of additional buildings could be indicated. The same Rn indicator approach could be considered for spatially and temporally guiding the CV sampling of these additional buildings.

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