U.S. EPA "State of VI Science" Workshop

Selecting Sampling Strategies for Efficient & Economical Vapor Intrusion Site Assessment & Long-Term Management – forming Soil Gas Safe Communities

Why Does the Radon Tracer Not Work All the Time?

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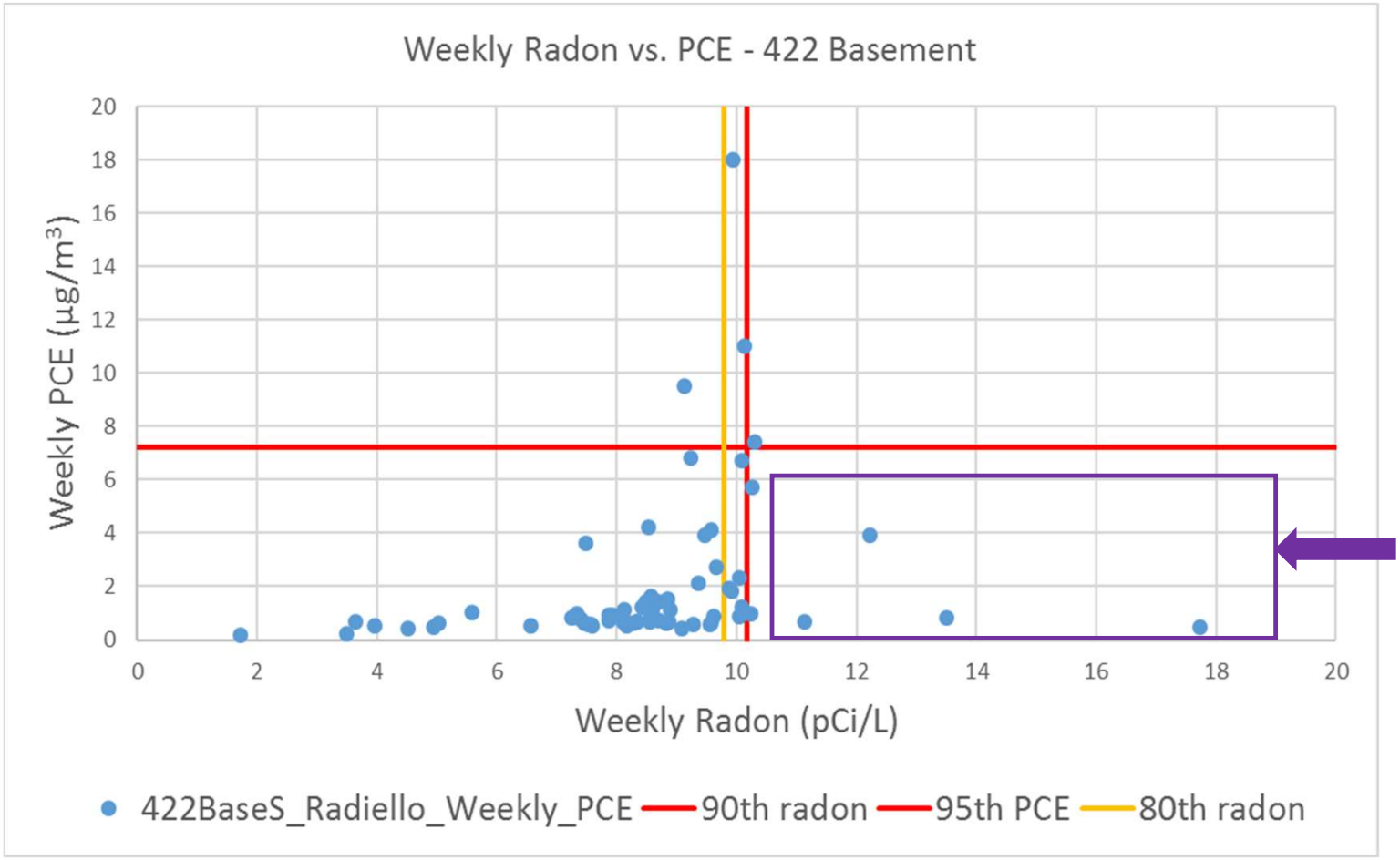
Objective

- Most previous studies have shown a statistically significant relationship between radon and VOC vapor intrusion, but not all.
- Examine in Detail why Do Radon and VOCs not Correlate as Well in One Well Studied Case: Indianapolis Basement?
- Why do some data points in the Sun Devil Manor (SDM) case fall far from an otherwise strong radon/VOC correlation line.

For radon to be a valuable tracer:

- Radon route and mechanism of entry should be similar to that of VOCs of interest, once both species are present in the subslab soil gas.
- Concentrations of radon and the VOCs of concern should be well correlated in subslab soil gas.
  - Not necessarily expected as radon and VOCs have different sources. May be approximately true if the VOC(s) of interest and radon are both widely dispersed in deeper soil gas. Then the concentrations of both radon and VOCs in the immediate subslab layer may be controlled by the ratio of flow from the deep soil gas to dilution air.
- Interior sources of radon should be negligible (generally true).
- The loss rates to sink effects (sorption to building materials) in the indoor environment should be similar or negligible for radon and VOCs, so that the air exchange rate forms the primary control of indoor air concentration once soil gas has entered the building.
- Implies that subslab attenuation factors for radon and VOCs are similar.

Radon vs. PCE in Indianapolis, Heated Side, South Basement, Showing 80th and 90th percentile Radon Cutpoints (Reprinted from Lutes, 2017)

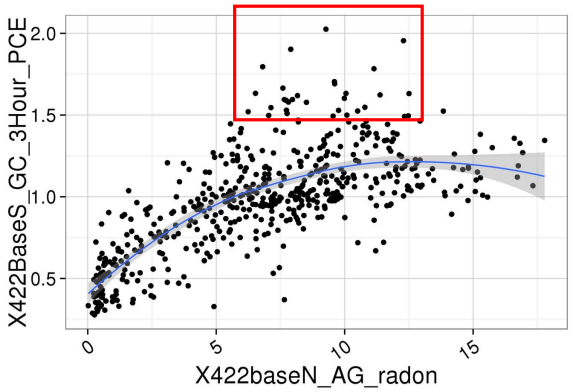


What is going on with these four data points that break up the trend?:
7/27-8/3/11
10/26 -11/3/11
7/20-7/27/11
2/16-2/23/11

PCE vs. Radon Do We See Correlation in in Basement: Various Time Scales

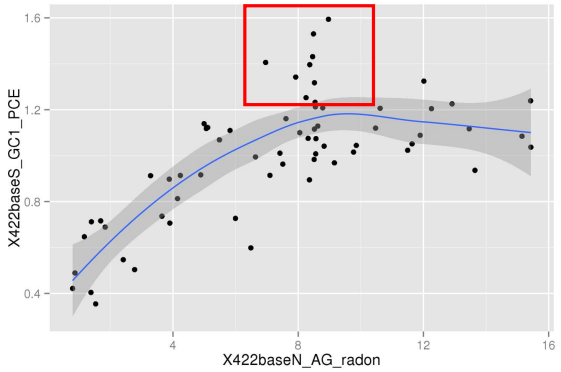
Key Point: PCE concentrations increase with Radon concentrations only to a point and then curve bends over.

Every 3 hours ↓



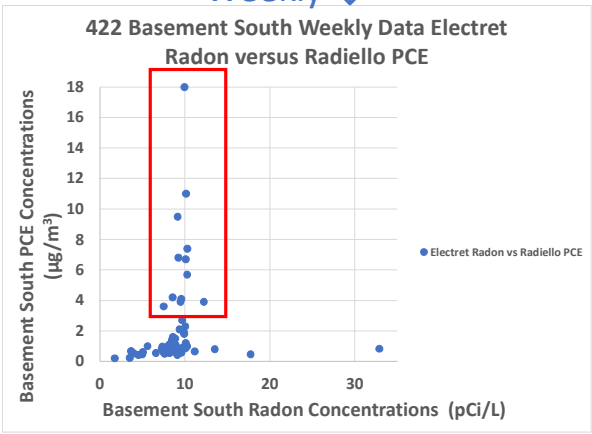
8/11/11-10/17/11

Daily ↓

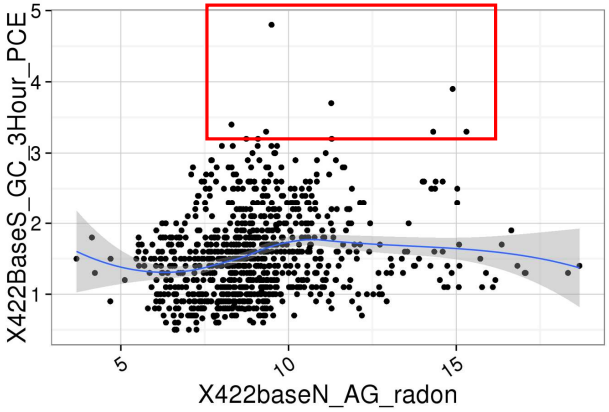


8/11/11-10/17/11

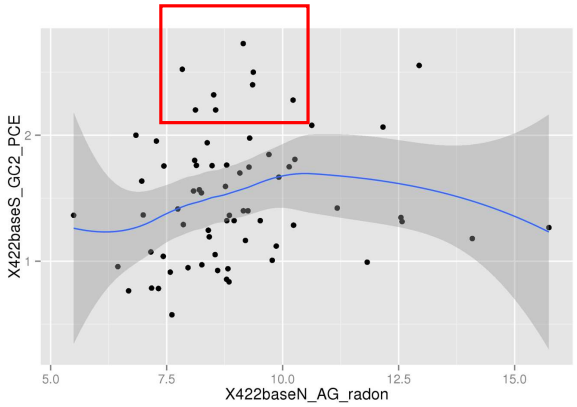
Weekly ↓



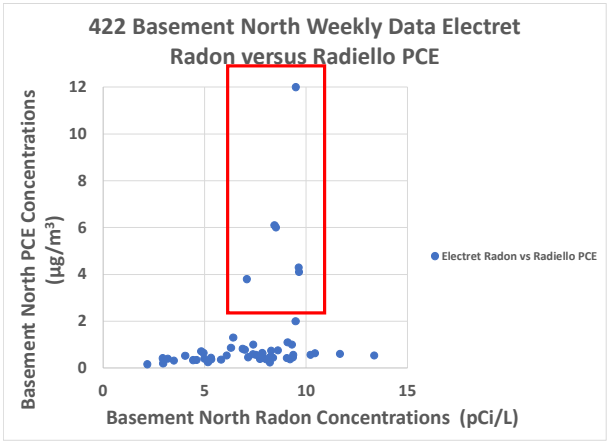
Long Period Base South



12/2/11 and 2/16/12

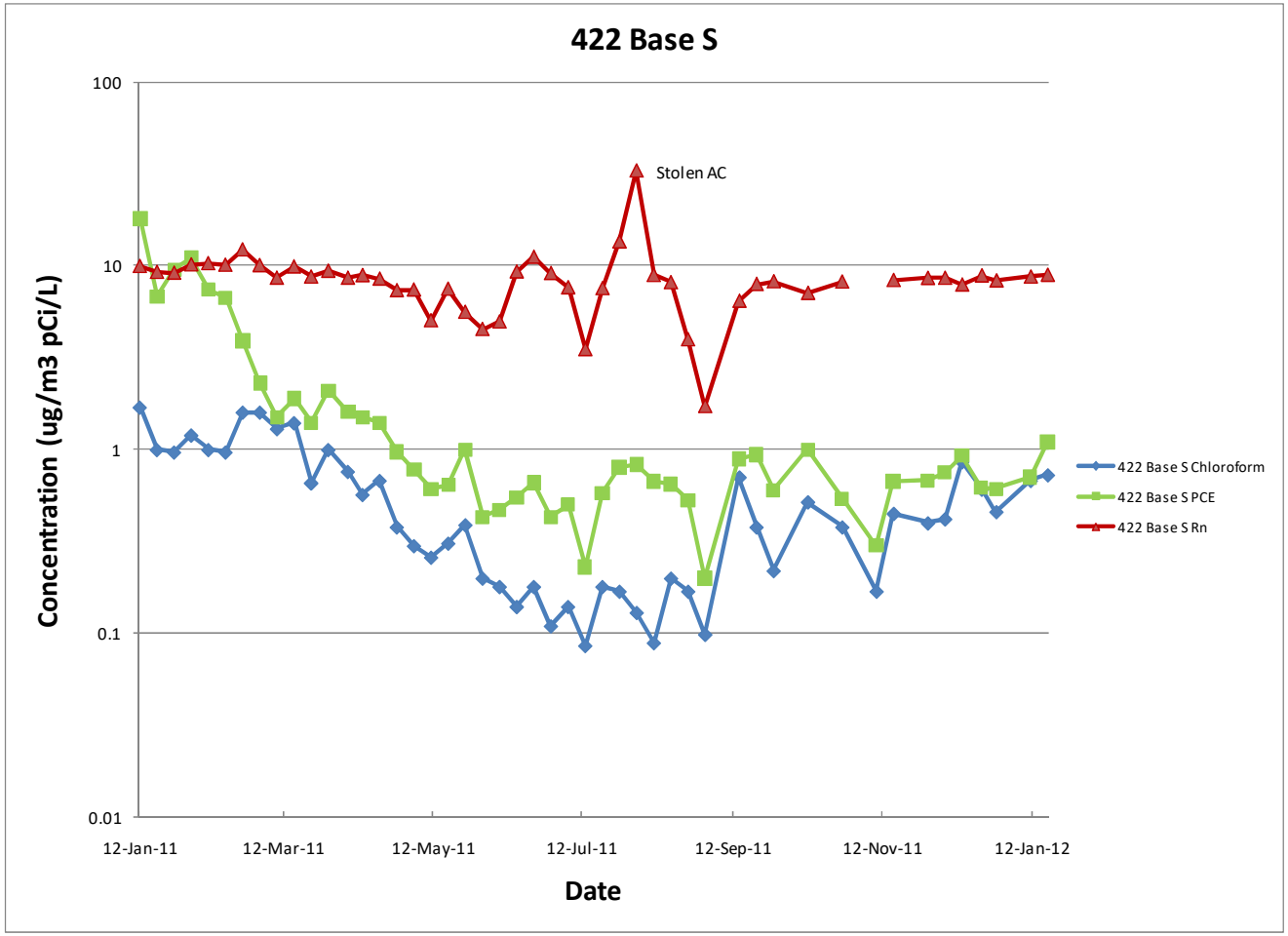


12/2/11 and 2/16/12



Long Period Base North

Radon vs. VOCs at Indianapolis Duplex, Basement, Heated Side, Weekly Time Integrated Measurements, Reprinted from Lutes 2012

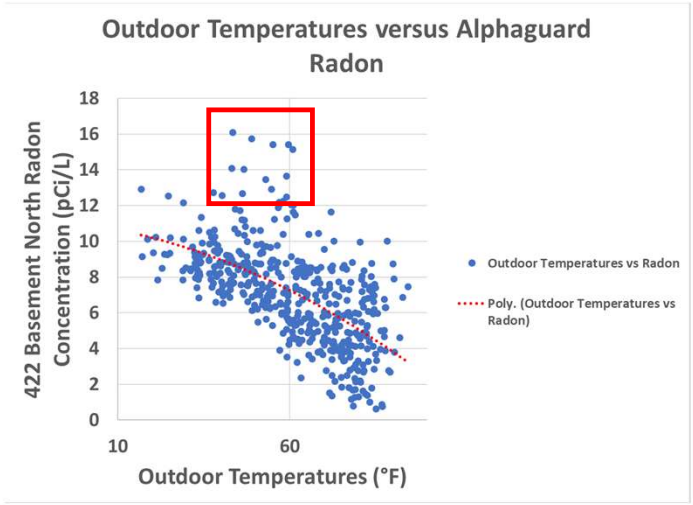


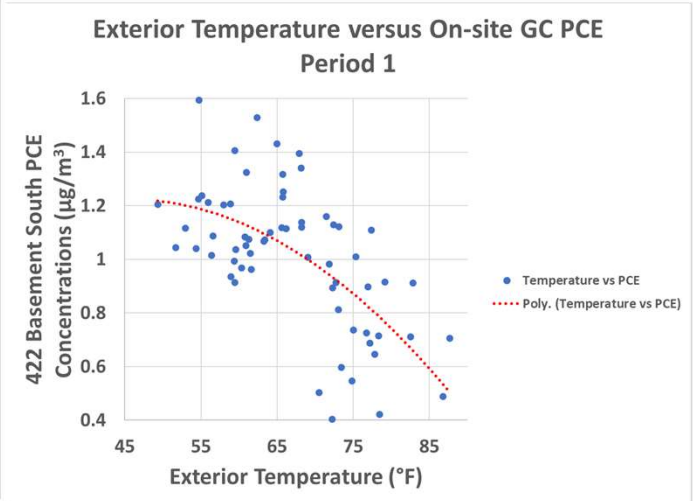
Note relative lack of seasonal change in radon…..

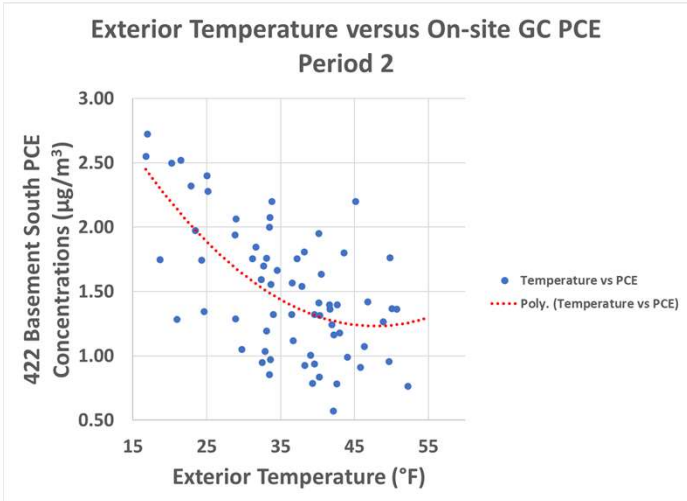
Possible evidence for depletion of VOCs from vadose zone in early months after HVAC installation. "Mining out of VOC mass in the yard".

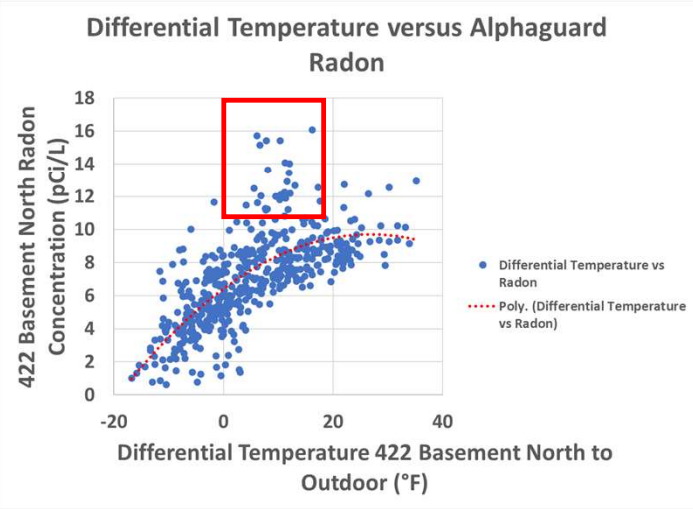
Figure 3: Temperature vs. Daily Radon (Alphaguard) and PCE in Heated Basement With Polynomial Fit

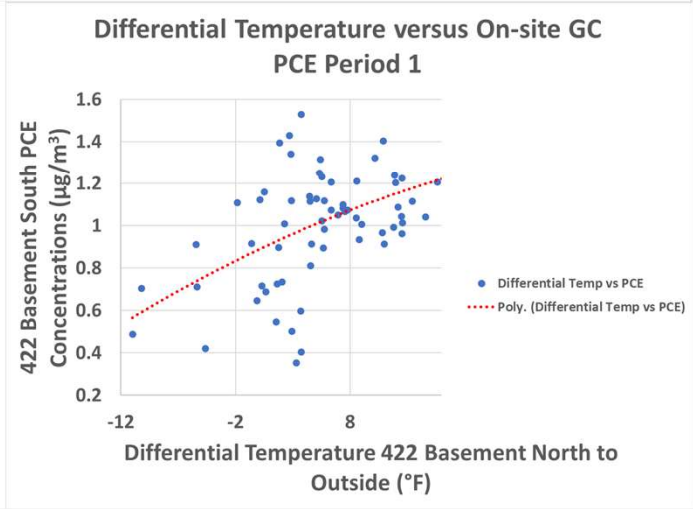
Key Point: Overall Trend Similar but peak radon associated with middle range temperature, peak PCE with lowest temperature











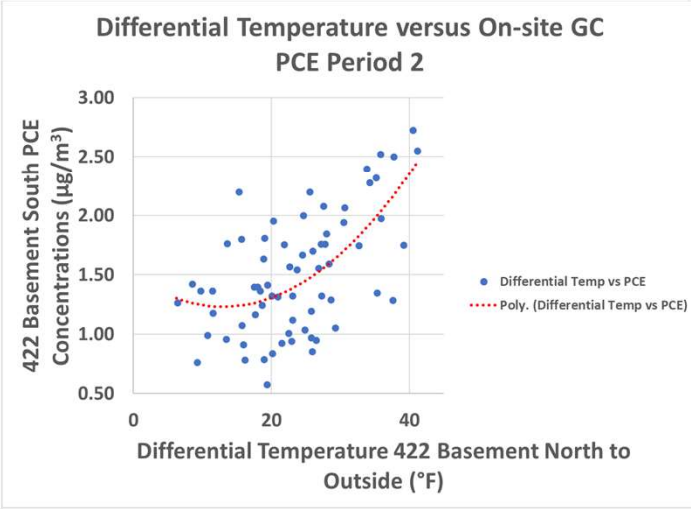
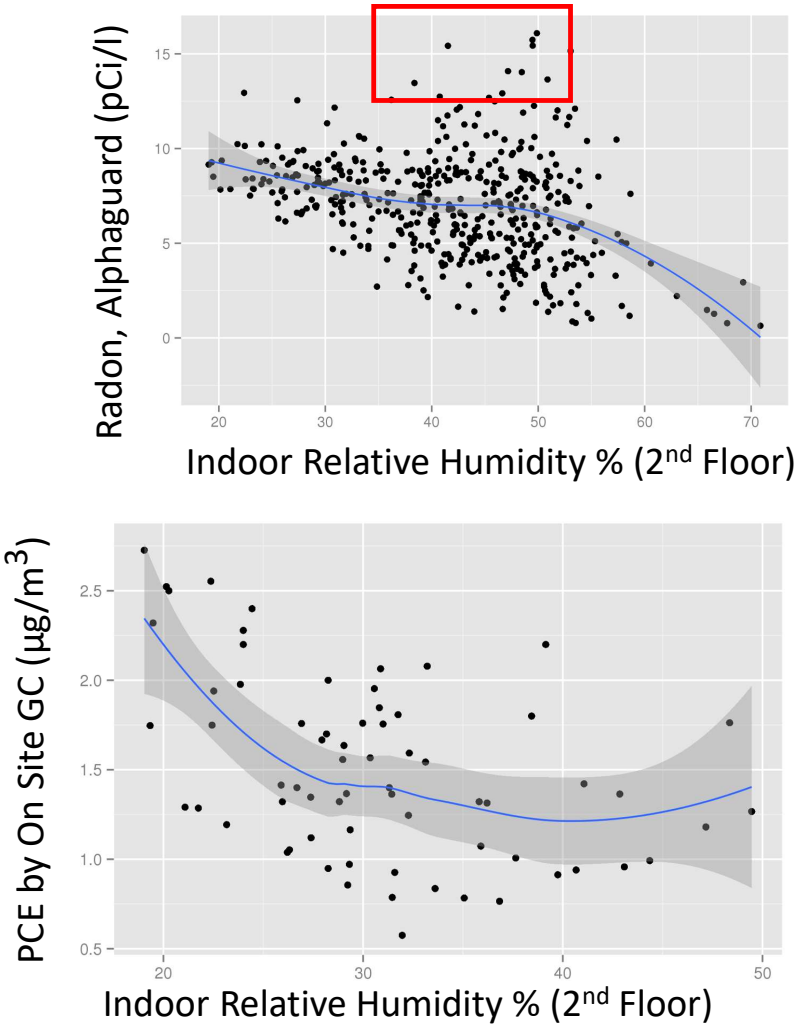
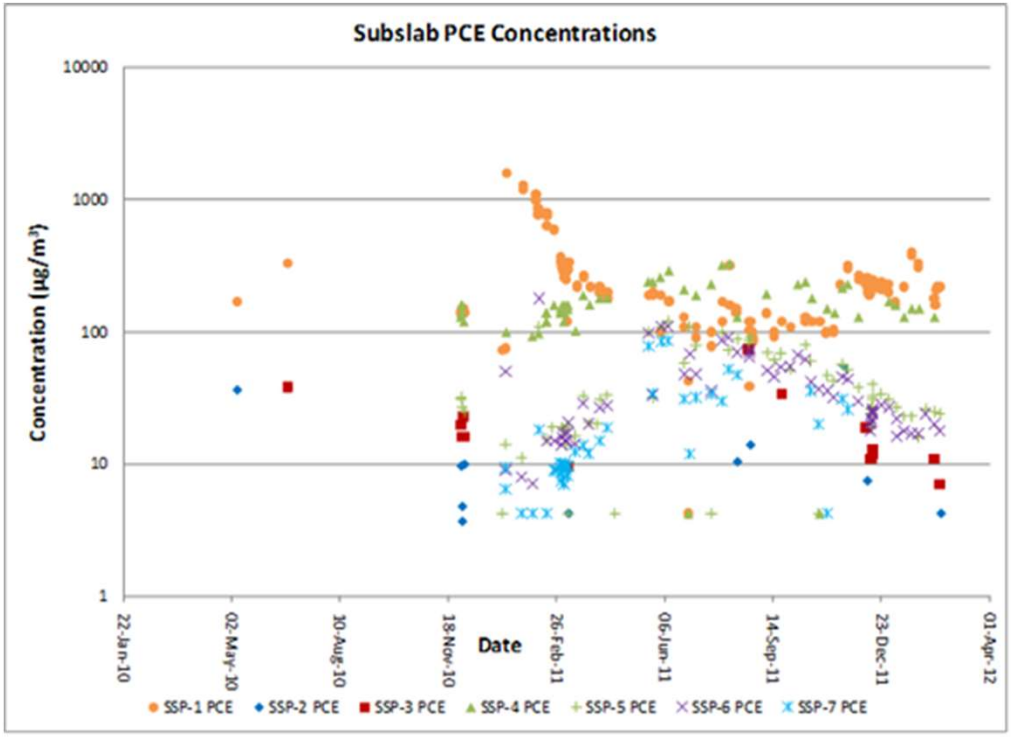


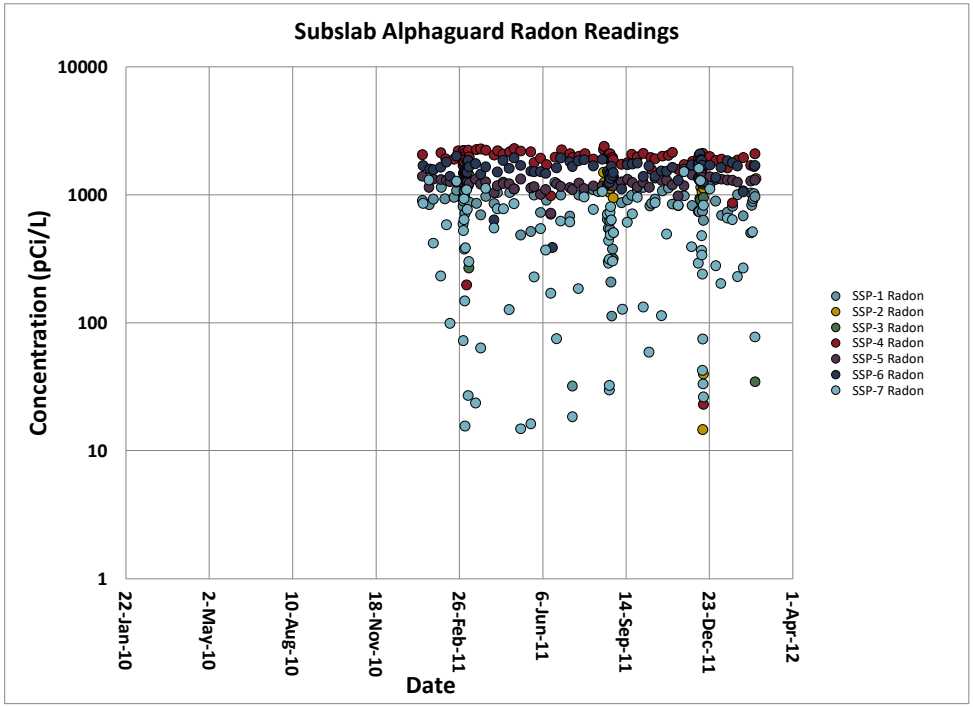
Figure 5: Radon and PCE vs. Indoor Relative Humidity Radon Dataset from March 31, 2011 through July 23, 2012; VOC Dataset from Dec 1, 2011 to Feb 26, 2012



Key Point: Peak radon associated with moderate indoor humidity. Peak PCE associated with lowest indoor humidity.

Figure S13 Subslab PCE Concentrations vs. Time, Reprinted from Figure 5-6a of EPA 2012 and adapted from Figure 5-39 in EPA 2012





Key Point: Strong seasonal variation in location of subslab VOCs under house. Subslab radon essentially constant vs. time in high concentration points. VOCs drawn toward center of heated side in winter.

Mechanistic Explanations for Temperature Behavior

(from Living Radon Reference Manual by Lewis and Houle)

- ***Temperature effects*** *produce two types of behavior in soils;*
  - *the first type is the widely observed diurnal variations that result from competition of convective flow due to temperature differences in soil from day to night and from turbulent mixing in the atmosphere, which leads to an increase in exhalation in daytime and a reduction at night.*
  - *The second type of behavior results from the direct heating of the soil (Collé et al., 1981). Stranden et al., 1984 also found a temperature effect on soil radon exhalation, with an increase in exhalation with increasing temperature. Physical adsorption of gases on solids is known to be temperature dependent; therefore, an increase in temperature caused a decrease in the adsorption of radon on the soil grains, with an increase in exhalation……*

Summarizes *Chittaporn, et al. showed that variability of basement radon was associated with* ***air exchange rate****. The lowest air exchange rate was during highest outdoor temperature (summer) and the basement radon was the highest. Conversely, colder outdoor temperatures yielded larger pressure differences yet lower basement radon concentrations.*

https://aarst.org/proceedings/2009/A_LIVING_RADON_REFERENCE_MANUAL.pdf

Mechanistic Explanations for Moisture/Humidity Trends

Living Radon Reference Manual (Lewis and Houle)

Summarizes *Stranden et al., 1984*

- *Three major effects of soil moisture causing an **increase** in radon exhalation; the direct recoil fraction of the emanation power is increased when there is a fluid present in the internal pores of the material, the fluid may hinder adsorption of radon gas on internal surfaces of the material, and with a soil moisture content gradient in the sample, active transport of radon on water molecules may take place.*

- *On the other hand, water present in the internal pores reduces the diffusion of radon out of the material. The radon diffusion coefficient for water is 0.00001 cm^2 sec^{-1} compared to the radon diffusion coefficient for air, which is 0.01 cm^2 sec^{-1}.*

- *Thus, up to a certain point of soil moisture content the increasing effects are dominating. After an optimum moisture content the reduced diffusion due to the water will dominate, and exhalation will decrease.*

https://aarst.org/proceedings/2009/A_LIVING_RADON_REFERENCE_MANUAL.pdf

Indianapolis Summary

- PCE and chloroform seem to peak at high but not the highest radon (10 pCi/l)

- This general shape/pattern holds with multiple data sources (Radiello vs GC for VOCs and Electret vs. Alphaguard for Radon).

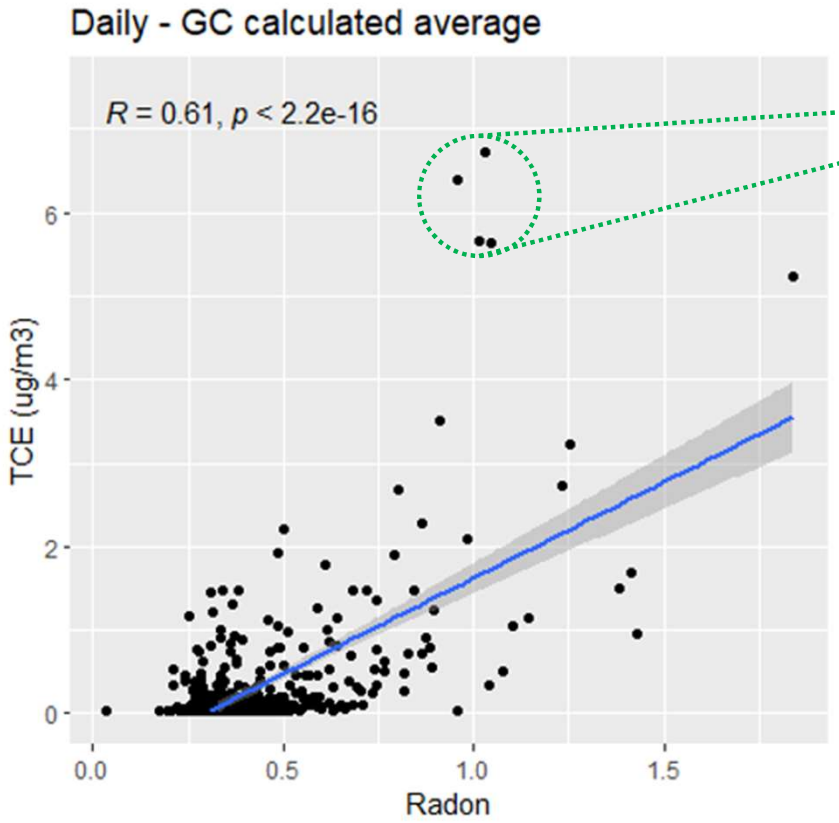
- While indoor PCE concentrations are maximized at low exterior temperature and low humidity conditions, radon concentrations peak under moderately cool and moderate humidity conditions.

- Subslab PCE concentrations were concentrated under the heated portion of the duplex during winter, while radon concentrations remained relatively constant over the seasons and across the building.

- Temperature is generally a more reliable I&T in the Indy basement

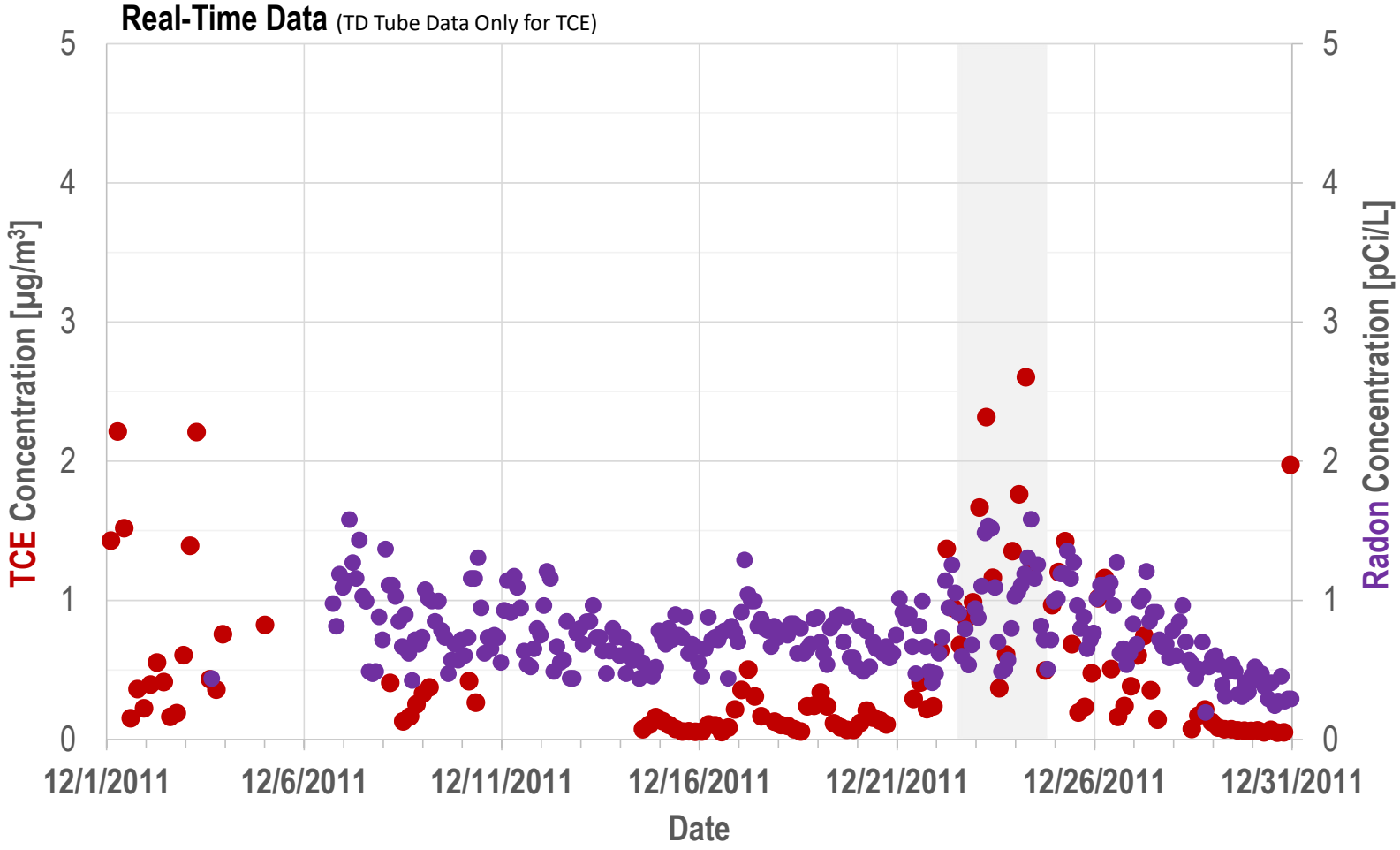
Sun Devil Manor Section

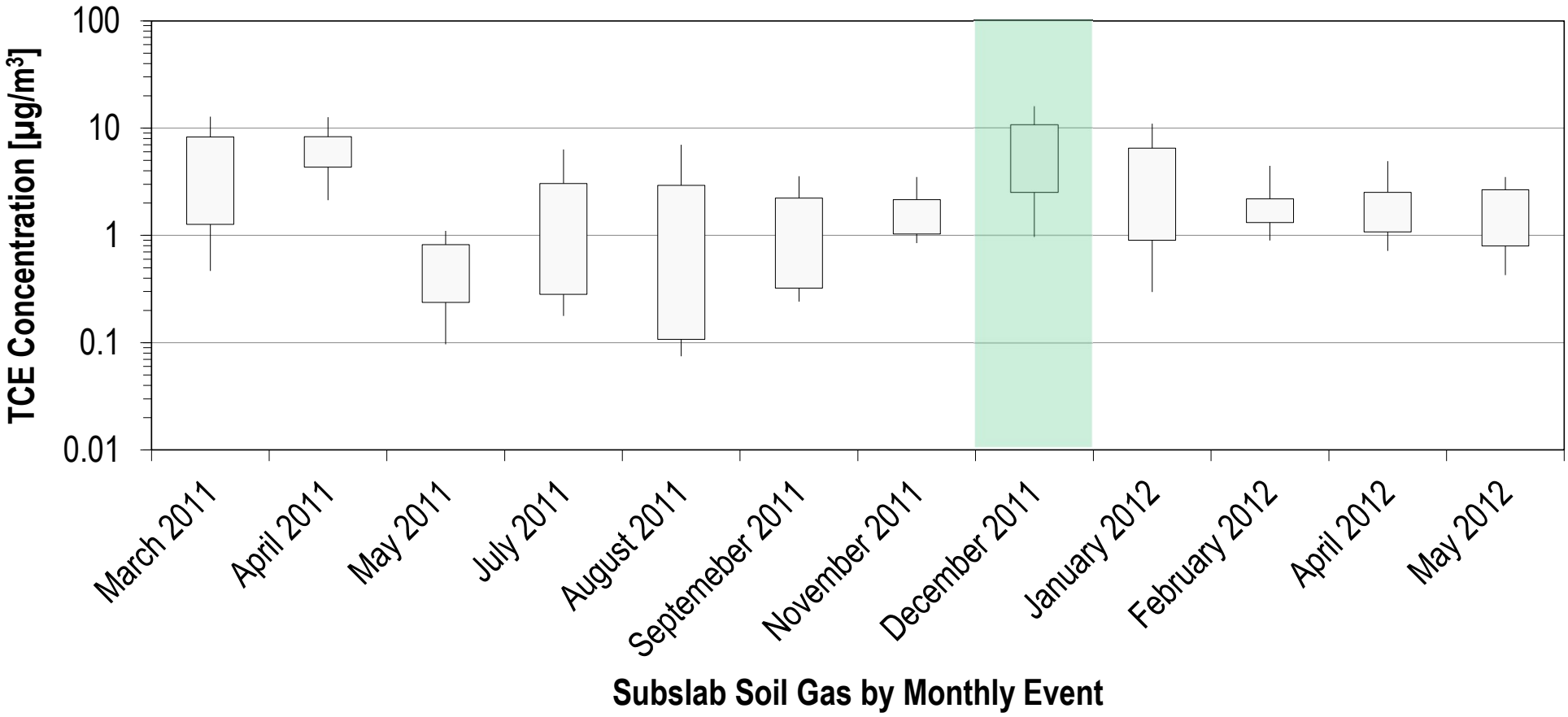
High TCE When Radon is not (Proportionately) as High

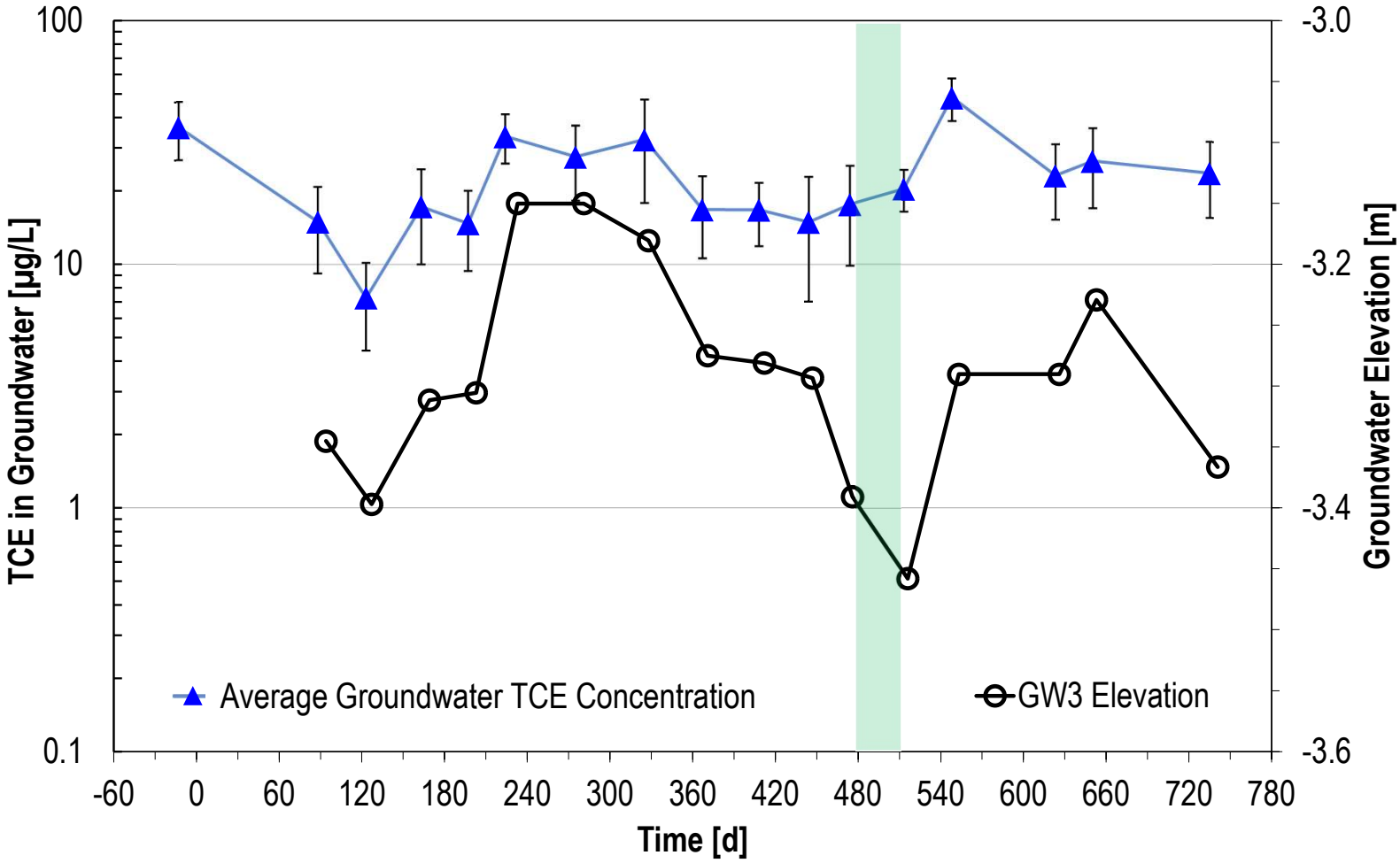


Date	Daily Averaged TCE Conc. [ug/m^3]	Daily Averaged Radon Conc. [pCi/L]
12/6/2011	6.85	1.02
12/22/2011	6.52	0.85
12/23/2011	5.73	0.98
12/24/2011	5.78	1.03

TCE and Radon vs. Time, December 2011




TCE Concentration [µg/m³]
100
10
1
0.1
0.01
March 2011
April 2011
May 2011
July 2011
August 2011
Septemeber 2011
November 2011
December 2011
January 2012
February 2012
April 2012
May 2012
Subslab Soil Gas by Monthly Event


100
10
1
0.1
TCE in Groundwater [µg/L]
-3.0
-3.2
-3.4
-3.6
Groundwater Elevation [m]
-60
0
60
120
180
240
300
360
420
480
540
600
660
720
780
Time [d]
Average Groundwater TCE Concentration
GW3 Elevation

For further Information

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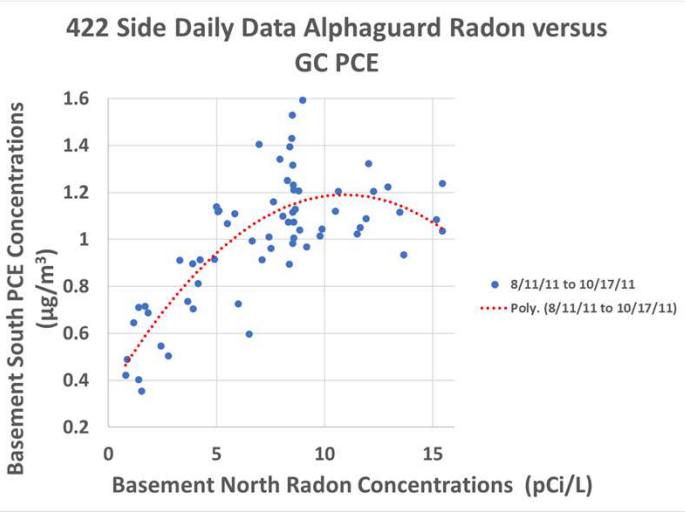
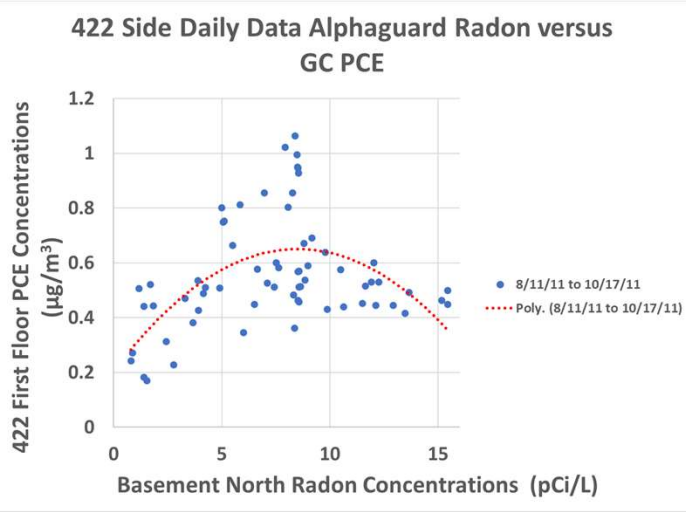
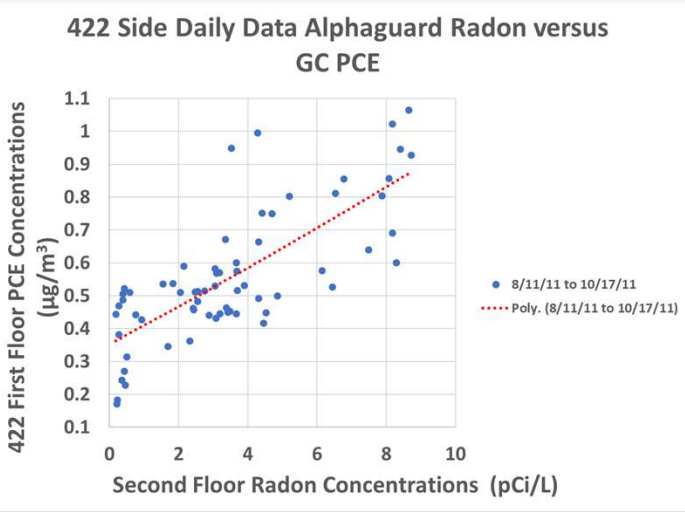
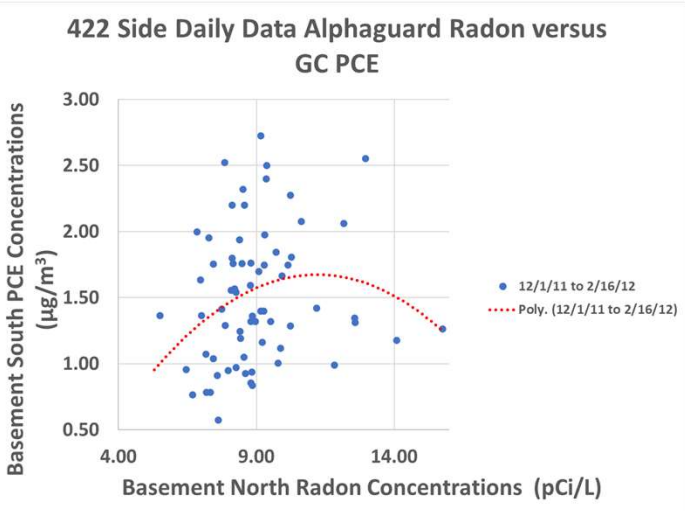
Data Set→ Weather Parameter ↓	Peak for Radon Daily 422 Base North (3/11/11 through 7/23/12)	Peak for PCE Daily 422 Base South 12/2/11 to 2/16/12	Can We Explain This From Theory?
Differential temperature	6-17 F at 22 Base South 7-17 F at 422 Base North	33-42 F at 422 Base South 28-35 F at 422 Base North	Yes, for VOCs stack effect strength controls. For radon increasing exhalation and decreasing sorption under warm conditions controls. Likely a balance of effects on Qsoil and Qbuilding, effected by leakage areas/locations. Subslab distribution changes for VOCs and radon differently over year.
Outdoor temperature	40-60 F	15-25 F	
Relative Humidity Indoor	42-53%	17-25%	Yes, for VOCs soil permeability controls, for radon due to moisture effects on emanation and exhalation rates.
Subslab moisture	130 cbar	135-137 cbar	
Basement to Outdoor differential pressure	Essentially neutral	< - 3 Pa	One possible explanation is that radon reaches a peak under conditions of very little flow, due potentially to diffusion. VOCs may be peaking under more classical stack effect conditions.
Basement to upstairs differential pressure	+0.2 Pa	> 0.7 Pa	
Deep soil temperature (16.5’ beneath structure)	15.6 – 16.4 C	14.9-15.1 C	
Wind Direction	West or Northwest	Northeast or West	
Peak Wind speed	24-33 MPH	Not clear but most in 15-25 MPH range	Likely a balance (per Song) of effects of wind speed on Qsoil and Qbuilding, effected by leakage areas.
Snowing?	Not for top six concentrations but yes for some of the higher.	YES - for all of the top six	Unclear, this may be a symptom not a cause – for example connections between synoptic snow events, barometric pressure drops followed by very cold arctic air.

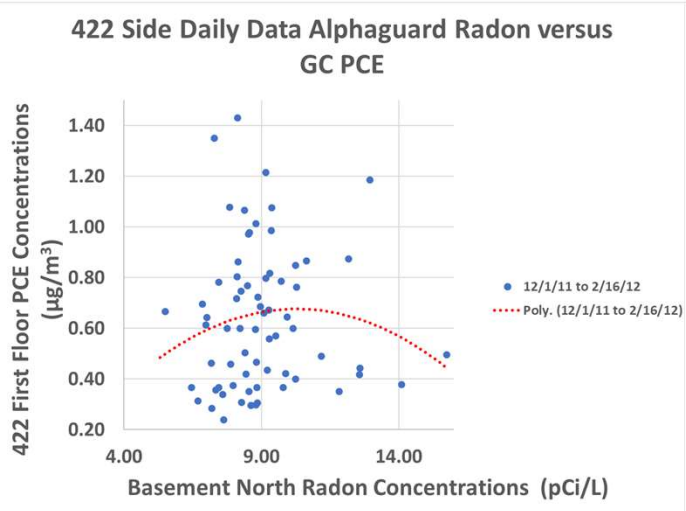






Daily Average Radon vs. VOC With Polynomial Fits Comparing Basement to First Floor





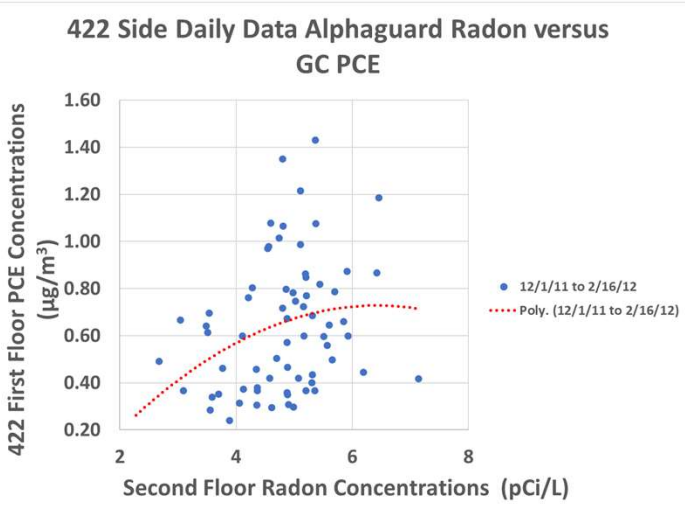
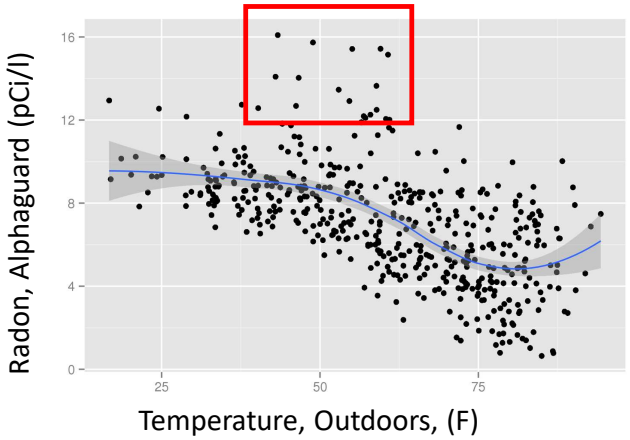


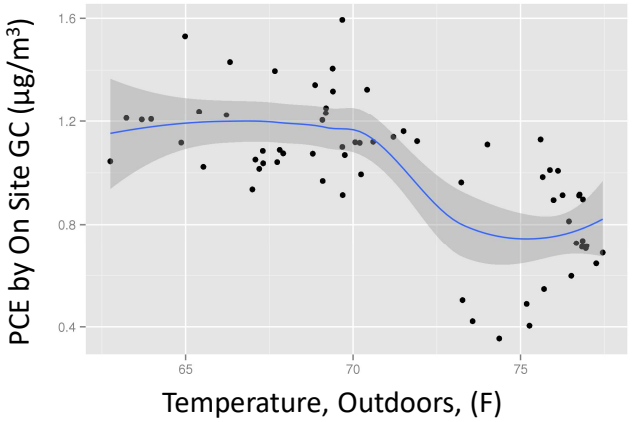
Figure 3: Temperature vs. Daily Radon (Alphaguard) and PCE in Heated Basement With LOESS Fit

Key Point: Peak radon associated with middle range temperature, peak PCE with lowest temperature

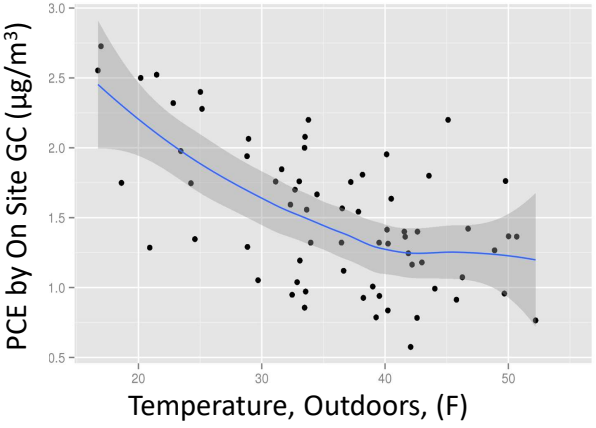
March 31, 2011 through July 23, 2012

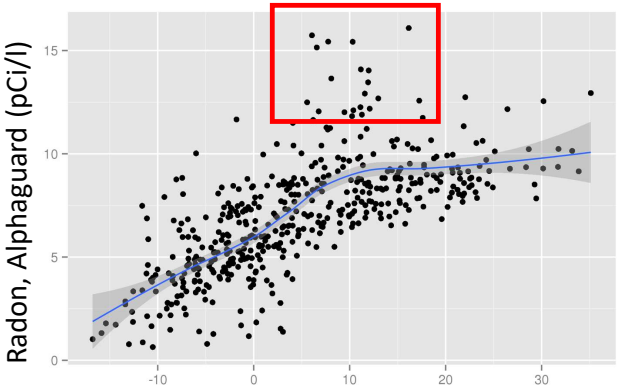


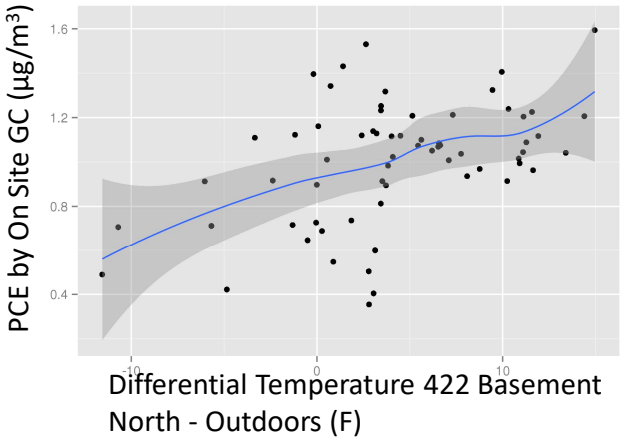
Aug 11, 2011 – Oct 17, 2011

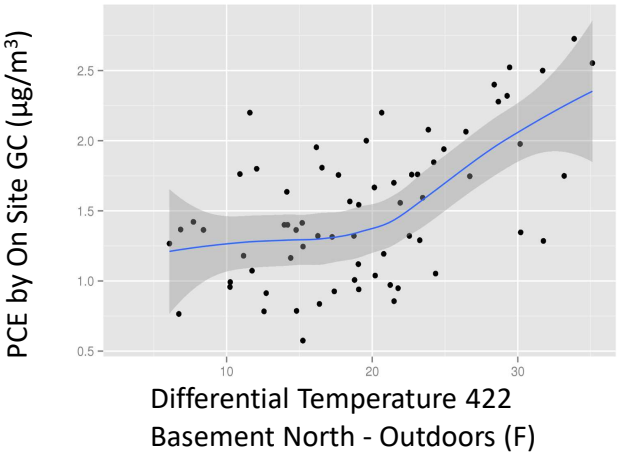


Dec 1, 2011 to Feb 26, 2012









Situation/Observation	Likely Dominant Mechanisms	Potentially Useful ITS	Reference
<u>Source Building:</u> Contaminants were released directly below the slab/floor of the building being studied	Diffusion from soil or building materials, soil temperature, moisture in the shallow soil layer which can control advective flow.	Soil temperature, soil moisture or CO_2 as a tracer of air exchange. Radon if distribution similar to VOCs (i.e. well mixed gravel layer)	Barnes and McRae 2017, Clausen 2019, Lutes 2021d, Levy 2021,
<u>Water Intrusion</u>: Water table variation so close to the structure that contaminated groundwater touches slab or directly enters.	When there is no vadose zone the standard assumptions about diffusion and then advection in the conventional VI pathway may not apply.	Water table height (depth to water in monitoring wells); visual observations of groundwater intrusion.	EPA 2015, Shen 2012, Illangasekare, 2014; Liu, 2021,
<u>Walk-out Basements or Large Open Doors:</u> Walk-out basements, buildings with large openings on one side only or VOCs released to soil immediately adjacent to one side of the building.	Situations where wind driven distribution of subsurface contaminants and driving forces are expected to be particularly important. The literature shows that soil gas VOC concentrations can be moved around beneath the slab by wind and that the location of strong differential pressure driving forces into the house can also be wind direction based.	Wind direction, radon, CO2 a tracer of air exchange	US EPA 2012a, Shirazi and Pennell 2017, Shirazi 2020, Guha 2011, Riley 1999
<u>Conduit VI:</u> Evidence of improper plumbing connections: odor of hydrogen sulfide, dry toilets, drain pipes open or stuffed with rags.	Direct intrusion of VOCs through sewer lines to indoor air may occur.	Hydrogen sulfide, visual observations of plumbing features, radon if sewers have soil gas intrusion	Nielsen, 2016; McHugh 2018; WI DNR 2021; US EPA 2012b; Pennell 2013, Kastanek 2016