INFLUENCE OF OUTDOOR RADON LEVELS ON INDOOR RADON LEVELS

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ABSTRACT

In the United States, the 1988 Indoor Radon Abatement Act goal was to reduce radon concentration in homes to outdoor levels. Meeting this goal has not been practiced by the industry primarily because it required making outdoor radon measurements and eliminating all radon gas entry into the residence coming directly from soil gas. In this study the reduction of typical indoor radon entry was maximized to the point where outdoor radon levels became the primary source. The methods used to eliminate the typical pathways of soil gas into the residence including radon flux through the slab were discussed. Continuous hourly radon measurements were made in the basement, first floor, second floor and outdoors from February of 2022 to February of 2023. Weather data was also collected and compared to outdoor radon levels. The comparison of the indoor radon levels to outdoor radon levels was used to determine the influence of outdoor radon levels on indoor radon levels.

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1.0 Study House Mitigation

1.1 Description of Study House

The house included in this study is located in eastern Pennsylvania in a new development of about 80 homes. The home is a traditional two story colonial with a walkout basement and a three-car garage. The home was built in 2015 and included a three-inch passive radon vent from the sump pit to the roof. The foundation walls are 10-inch poured concrete. The front entrance is a six-foot wide concrete slab, one step down from the main house floor. The garage-slab is three-steps down from the main house floor. Before the new owners occupied the house, in late 2015, the radon levels in the basement measured around 1400 pCi/L. The central area of the development where this home is located had 18 other homes that were greater than 1000 pCi/L when measured before occupancy and any active system was installed.

1.2 Active Soil Depressurization Mitigation System

Figure 1 depicts the radon mitigation system and the final sub-slab pressure readings in pascals (Pa). The initial mitigation system activated the three-inch passive radon pipe with a GBR45 fan installed in the attic and an additional three inch passive jumper pipe routed from the basement sub-slab to the garage sub-slab. The basement sub-slab vacuum was negative 4.2 pascals. The post mitigation radon test was 4.3 pCi/L. A three-inch jumper pipe was then routed from the basement sub-slab to the front entrance sub-slab. The radon results came back at 1.9 pCi/L. The homeowner then reported a level of about 5 pCi/L from his home safety radon monitor. A second sub-slab depressurization system was installed on the front side of the home using an RP145 fan installed outside with the exhaust routed above the roof. The fan was later changed to a Fantech RN3 fan. This system included a new suction into the basement sub-slab and direct suction into the garage sub-slab. The pressure readings under the slab, which were measured with an Energy Conservatory DG700 micro-monometer, are shown in Figure 1. The lowest sub-slab pressure reading was negative 27 pascals. Over the next few years, the homeowner reported that his radon monitor was recording levels above 4.0 pCi/L, especially in the summer. This started the diagnostic investigation in 2021.

Two methods were considered as options to further reduce the radon levels. One was to determine if radon was fluxing though the slab. The other consideration was to add additional ventilation to the basement using either an energy recovery ventilator (ERV) or a heat recovery ventilator (HRV).

1.3 Study House Sub-Slab and Flux Measurements

Flux measurements of the basement slab were made in multiple locations to determine if the sub-slab was contributing a significant amount of radon to the basement. An important reason to make these measurements in multiple locations was to determine if there were large variations in the slab flux. The results of the grab samples and sniffer measurements are displayed in Figure 2. These sub-slab measurements show a range from 54 pCi/L to 5300 pCi/L, with the results indicating that most of the sub-slab had sub-slab radon levels greater than 2000 pCi/L.

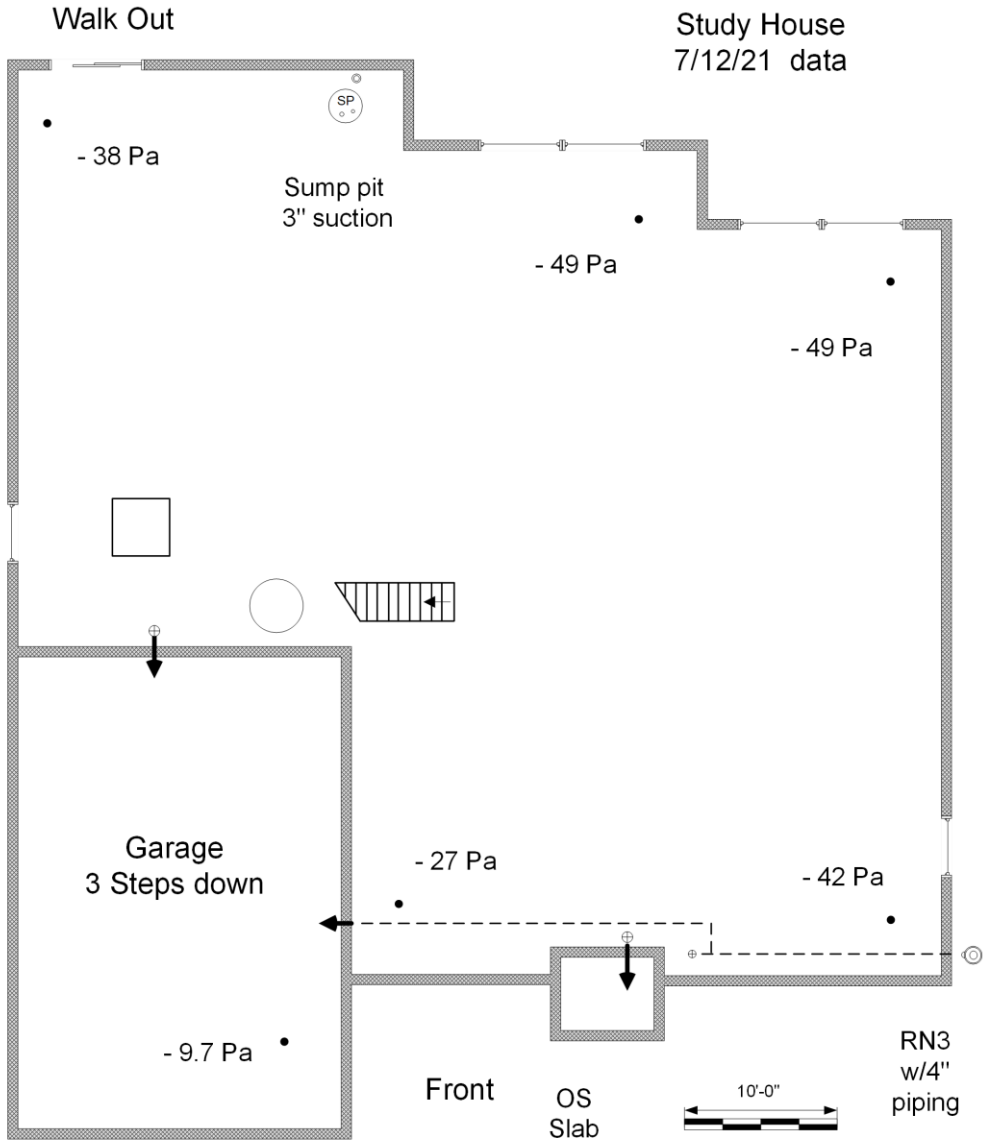

Figure (1): Study house mitigation system layout and sub-slab pressures

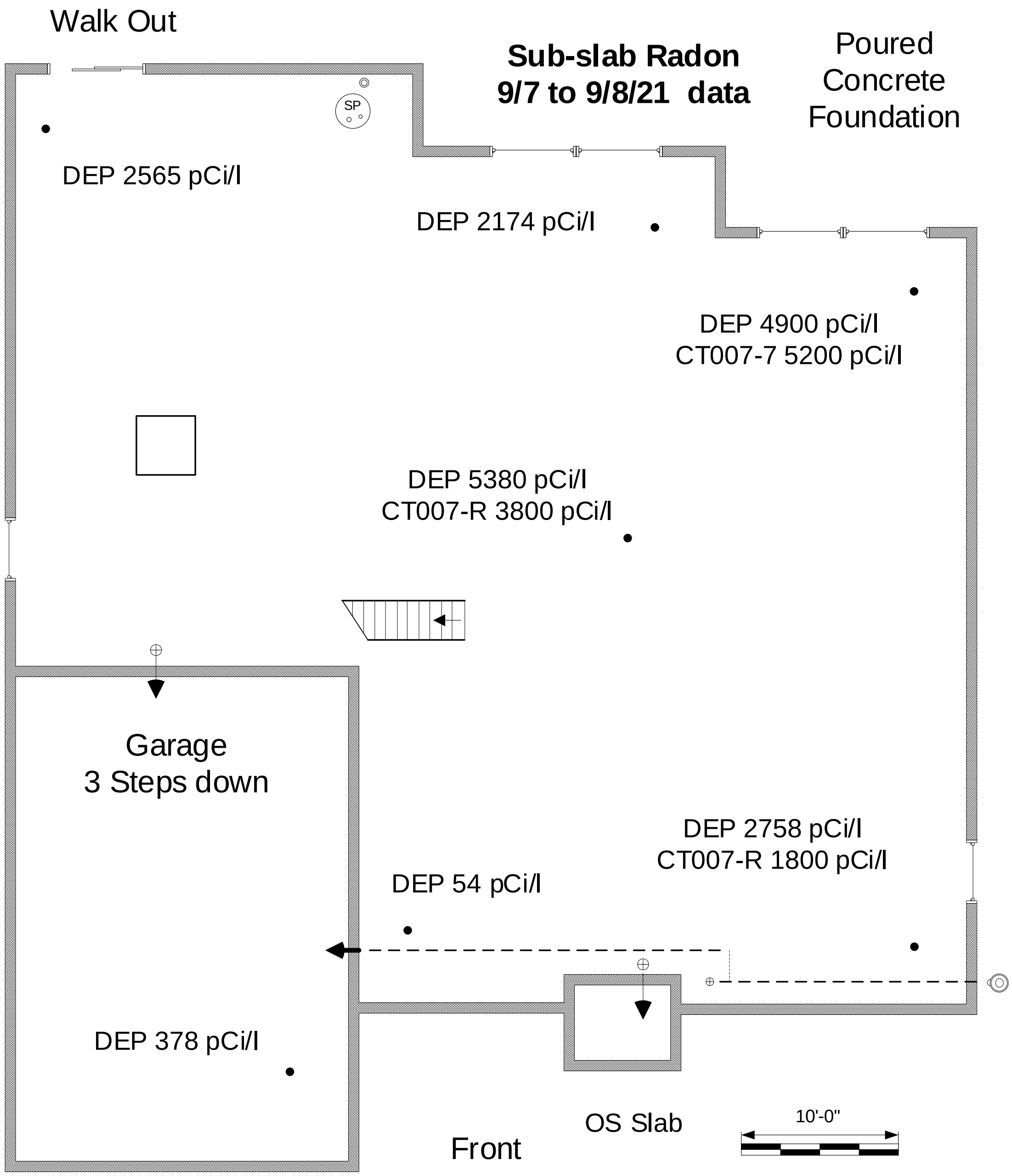

Figure (2): Sub-slab radon measurements made with
PA DEP grab cells and WPB radon CT007-R radon sniffer

The radon levels under the slab were measured with Pylon scintillation cell grab samples taken in five locations under the slab by the Pennsylvania Department of Environmental Protection (PA DEP) radon division. On the same day, the Environmental Instruments of Canada CT007-R was used to make similar sub-slab radon measurements at three PA DEP test locations. The results of those measurements are included in Figure 2. The variation in results between the PA DEP grab samples and CT007-R was likely due to sampling technique as well as variability of the radon monitors. The sampling method required minimizing the portion of time the sampling test holes were open to the basement air because the strong negative pressure in the sub-slab would backflush the sub-slab radon concentration with low radon basement air. Another concern with making direct sub-slab sniffer measurement is that the presence of thoron will lead to erroneous high values for radon concentration. Radon system exhaust in Pennsylvania and New Jersey had been measured to be greater than 80% thoron at some locations. (Brodhead, 1993) The CT007-R has a thoron-measuring function which should be used when making direct soil measurements to determine if a significant amount of thoron is present in the soil. In this study, a separate Pylon scintillation cell was used and set to 30-second intervals to measure the fall-off of counts when sampling had been completed. No significant fall-off occurred indicating there was very little thoron in the sub-slab air. If thoron were present, the CT007-R reading would have biased significantly higher than the PA DEP grab samples, which did not appear to be the case.

Figure (3): Grab sample with CT007-R

Figure (4): EcoTracker and battery placed in metal bowl

Figure (5): Flux test run for minimum of 6 to 12 hours

Flux measurements of the slab were made using Ecosense EcoTrackers, placed under a three-liter stainless steel bowl with a 20,000 AH 5 volt battery and 5 volt to 12 volt inverter cable to power the EcoTracker. The edge of the bowl included an EPDM rubber gasket to provide an airtight seal. A weight was placed on the bowl to compress the gasket. The test needs to be run from 6 to 24 hours to obtain enough in growth to analyze the results. See pictures of the flux monitors in Figure 3, Figure 4 and Figure 5. The results of the flux tests both before the slab was coated with RadonSeal and after are displayed in Figure 6.

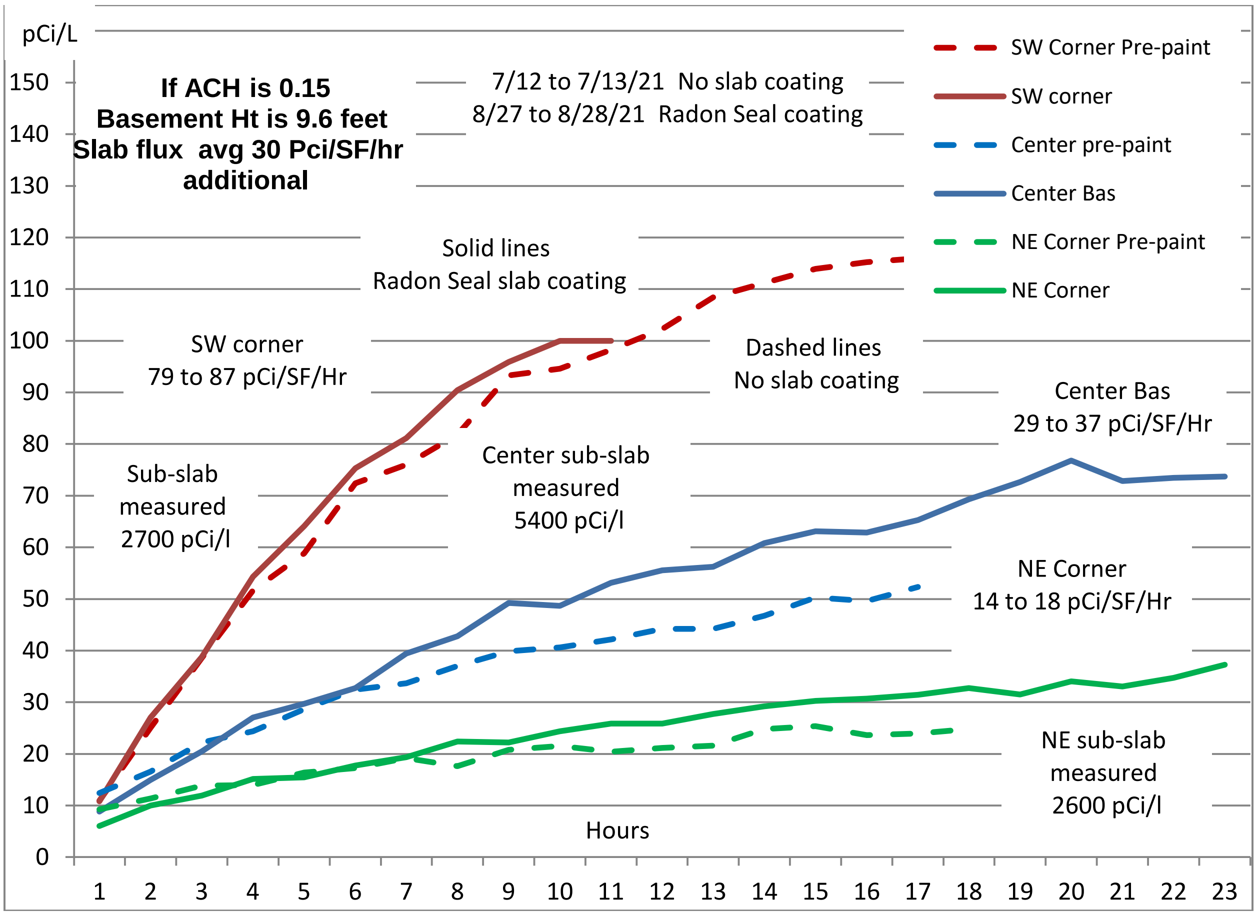

Figure (6): Flux test results before painting slab (dash lines)
and after painting slab floor (solid lines)

Once the flux test is completed the results were entered into a spreadsheet and then converted into a graph. The radon level change was then divided by hours the change took place, to give pCi/L growth per hour. To determine the radon emanation out of the slab the growth per hour was multiplied by the air volume of the bowl in liters (2.75 liters) which requires subtracting the material volume of the Ecotracker and the battery. This removes the liter component and gives a value of pCi/Hr growth. This result was divided by the slab square foot (SF) area the bowl covers (0.3068 SF) to give the pCi/SF/Hr radon flux out of the slab.

Flux measurements using the EcoTrackers were made before any surface coatings were applied to the slab. The owner agreed to apply a coating to the slab to reduce this transmission. The owner purchased 20 gallons of RadonSeal coating and spray applied two coats to the entire basement slab. The flux measurements were repeated in the same locations after the sealant had a week or two to dry. The dashed lines in Figure 6 were the pre-paint flux results. The solid lines were after the slab was sealed with two coats of RadonSeal. The graph indicates that no significant change in the flux was obtained by spray applying two coats of RadonSeal to the basement concrete slab.

During one of the rounds of radon testing a storm came through and the power was off for four hours. The basement radon rapidly increased, although it was not measured because the radon monitors lost power. When the power resumed, the radon monitor also resumed, and tracked the radon levels as they decreased. The rate of decrease took about 6.5 hours for the radon levels to be half the previous concentration. This is equal to approximately an air change per hour (ACH) rate in this basement of 0.15 ACH which is considered low but not unusual for a basement of a new home. To obtain the slab flux contribution to the basement radon levels, the square footage of the basement was multiplied by the approximate average flux rate that was measured in pCi/SF/Hr. This amount of pCi was then divided by the number of outdoor incoming liters of air per hour based on the calculated 0.15 ACH to determine the approximate radon contribution from the slab. Using 0.15 ACH and the results of the first round of flux tests, it was determined that the radon flux through the slab was contributing 0.75 pCi/L of radon to the basement radon levels.

1.4 Installation of HRV / ERV

The radon levels outdoors at this development have often exceeded indoor radon levels by a factor of 2 or 3 in the middle of the night when there is little or no wind. The elevated outdoor radon levels had been measured in the past and were found to be inversely correlate with wind speed (Brodhead ref 2). Increasing wind causes low outdoor radon levels and little or no wind allows radon levels to build up outdoors. Generally, no wind periods happen at night. The initial outdoor radon level testing at the study house was done in the rear of the house about 20” off the ground. A second outdoor measurement was made ten feet above grade on the upper main floor deck. The HRV was designed to draw air from beside the upper deck ten feet in the air with the concept that this location would have lower outdoor radon levels. Ecosense RadonEye RD200+ and RadonEye Pro detectors were used because they included a time clock that confirms the syncing of all the indoor and outdoor measurements. The radon monitors were placed in plastic mailboxes with holes cut in the bottom to protect them from rainfall. Additionally, the radon levels in the basement and first floor were also measured, as can be seen in Figure 8. The radon results in Figure 8 indicate little difference in outdoor radon levels between 20 inches above grade and 10 feet above grade. This indicates that when the wind stops, the radon emanating from the ground fills up the surrounding atmosphere like a swimming pool. Based on this small difference, the outdoor radon monitors used for the long term study were placed on the floor of the deck, ten feet in the air rather than at grade.

Figure (7): Rear of Study House - Outdoor levels measured at:
20” above grade under the deck and 10’ above grade, on the upper deck

The results depicted in Figure 8 indicated that an HRV or ERV could be used to lower the indoor radon levels only if run during daytime periods to avoid the evening times when outdoor radon levels tend to spike high. If the HRV/ERV was to start at 9 AM and turn off at 8 PM and the air was obtained from ten feet above grade, the average outdoor radon levels during that period would be 1.7 pCi/L. During the non venting period of 8 PM to 9 AM the average outdoor radon levels were often below 4 pCi/L but the average of 3.2 pCi/L was almost twice the daytime average. The suggested on times of the HRV/ERV are shown as dashed arrows on the bottom of Figure 8.

After a discussion with the homeowner about the HRV/ERV, they decided that they would like to first try coating the basement slab with an epoxy based paint rather than have the HRV/ERV installed. The owner decided to install the epoxy paint himself.

1.5 Epoxy Coating Basement Slab

The owner used multiple two-part kits of Rust-Oleum Rock Solid garage paint that were available from one of the large building supply stores. The epoxy kit required mixing the two components and applying in one continuous application. The epoxy coating was applied over the entire basement slab which had been previously double coated with RadonSeal. After it cured, there were several locations that had shrinkage openings in the epoxy coating (Figure 9).

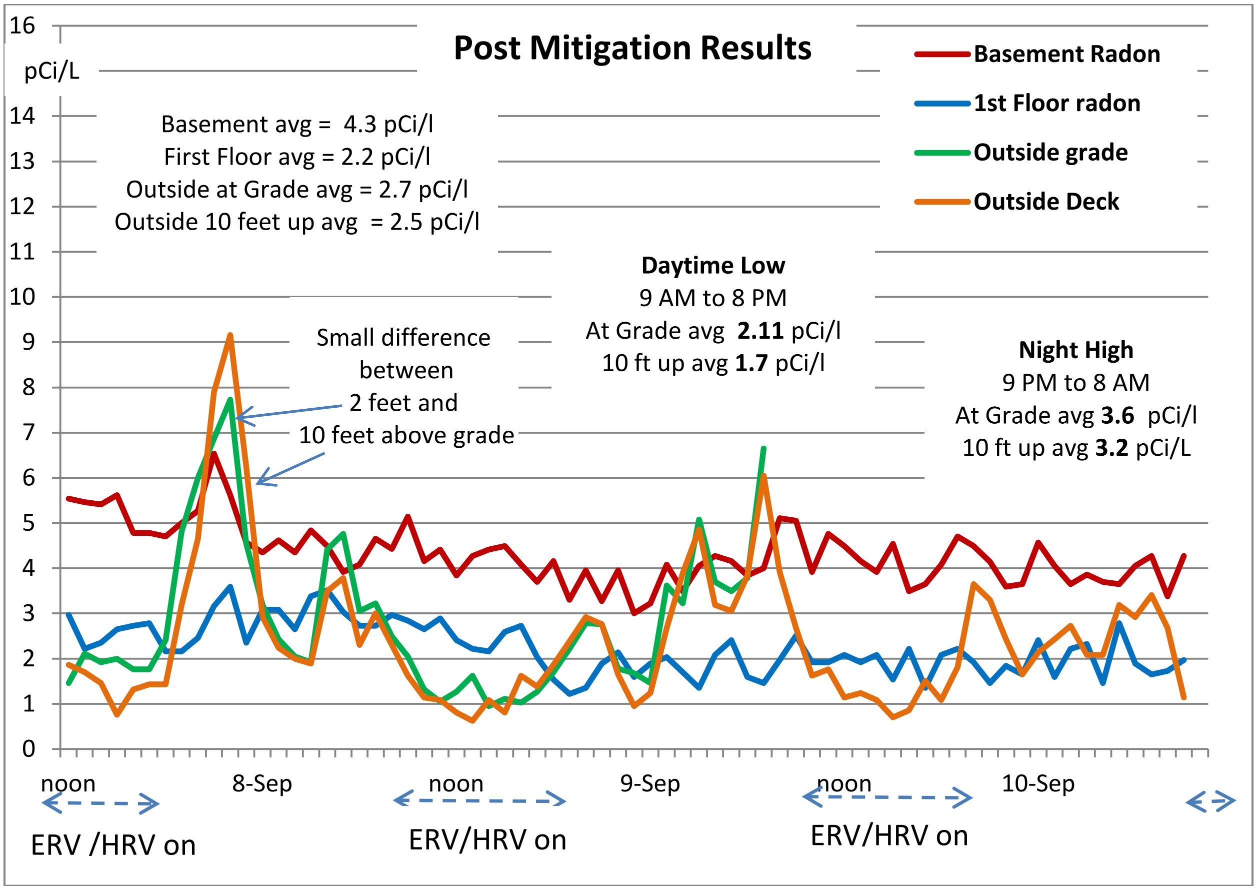

Figure (8): Indoor and outdoor radon results.
Outdoor radon 2 ft and 10 ft above grade track each other

Figure (9): Cracks in single application of epoxy

Two slab flux measurements were made after the first coating of epoxy was applied. One was over an area that had no visible cracking and the other was over one area that had cracking. The poured foundation walls were also fluxed in two locations. Figure 10 displays the flux of the poured walls in the green and blue lines. Although the walls showed some flux they appeared to be an insignificant contributor to the indoor radon levels. Figure 10 also displays the difference between flux measurements over paint with no cracks (solid red line) and paint that had cracks (dashed red line) as displayed in the photo of the slab in Figure 9.

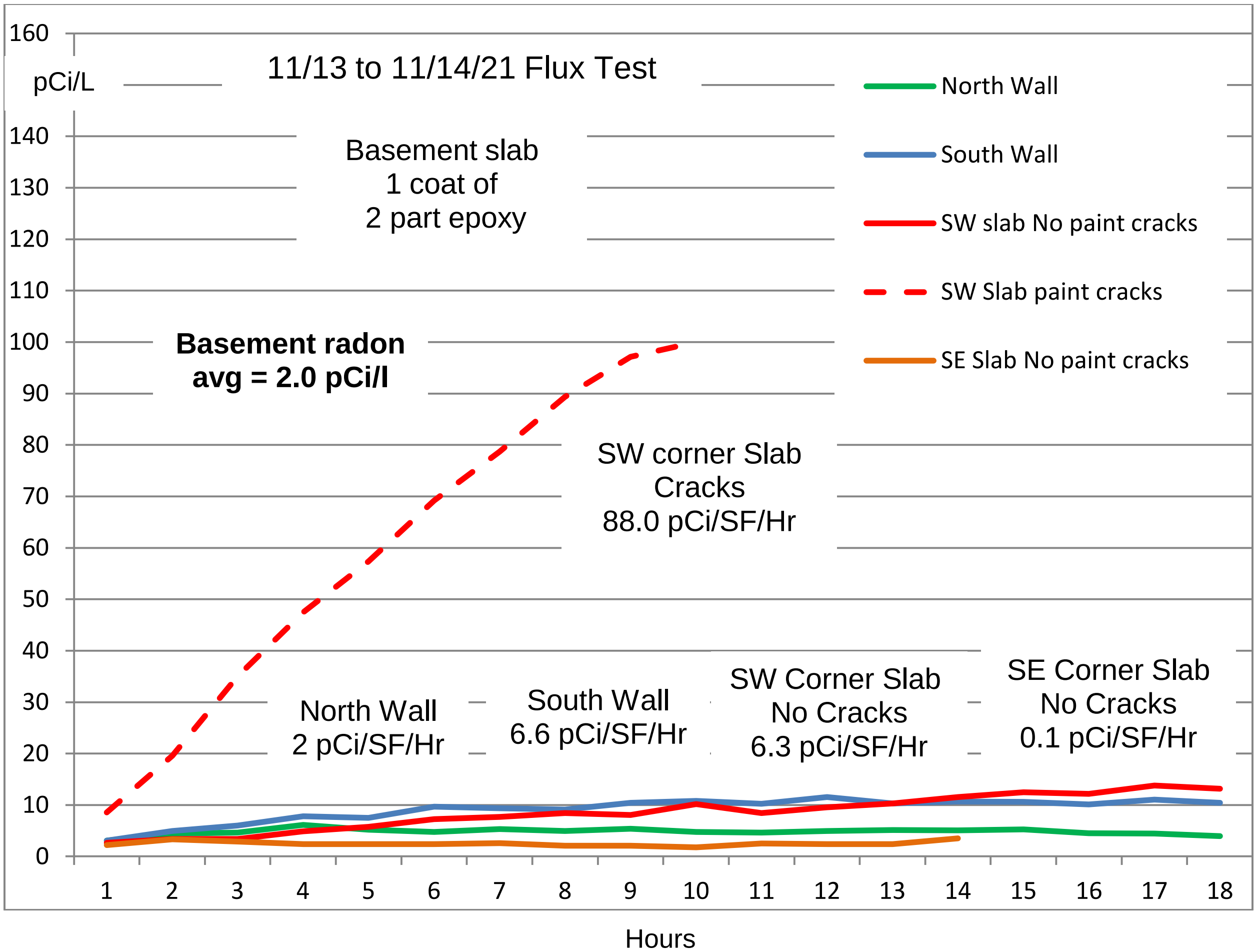

Figure (10): Flux testing slab after single coat of epoxy

After these results, the owner installed a second coat of epoxy paint. Figure 11 is a picture of the painted basement slab. Figure 12 displays the flux measurements after the second coat of epoxy was installed in comparison to the flux tests after two coats of RadonSeal was installed. After the second coat of epoxy was installed, the basement radon levels dropped to an average of 1.3 pCi/L. It appeared that the double slab coating of epoxy had provided three times the original predicted 0.75 pCi/L radon reduction.

Figure (11): Study house walk out basement with epoxy painted slab

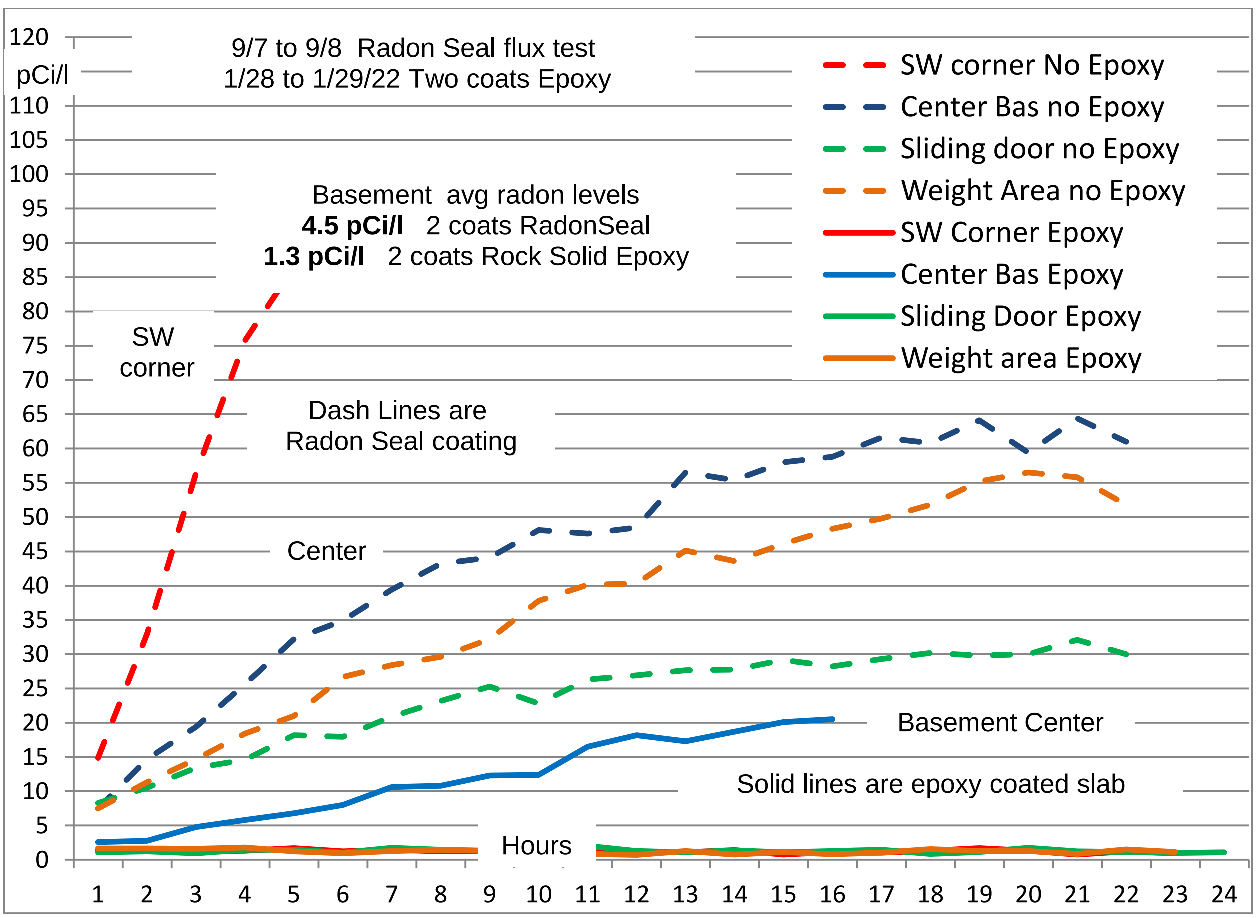

Figure (12): Flux testing slab after double coat of epoxy

The center flux test still showed significant flux after the two coats of epoxy were installed. What appears from this and from the cracked paint flux test was that even very small imperfections in the paint coating can significantly reduce the reduction of radon flux by the epoxy paint.

The slab was flux tested again in September 2022, about 8 months after the epoxy was installed, and the radon flux through the slab was barely measureable. As can be seen in Figure 13, there was no measureable flux through the slab even in the center flux test that previously was elevated. There does not appear to be any degradation in the epoxy performance after 8 months. A sniff measurement was taken in the center of the slab using the CT007-R. The sniffer measured about 3500 pCi/L under the slab. A year earlier in September 2021, the CT007-R measured 3800 pCi/L under the slab in the same location indicating very little change since the slab had been coated with epoxy.

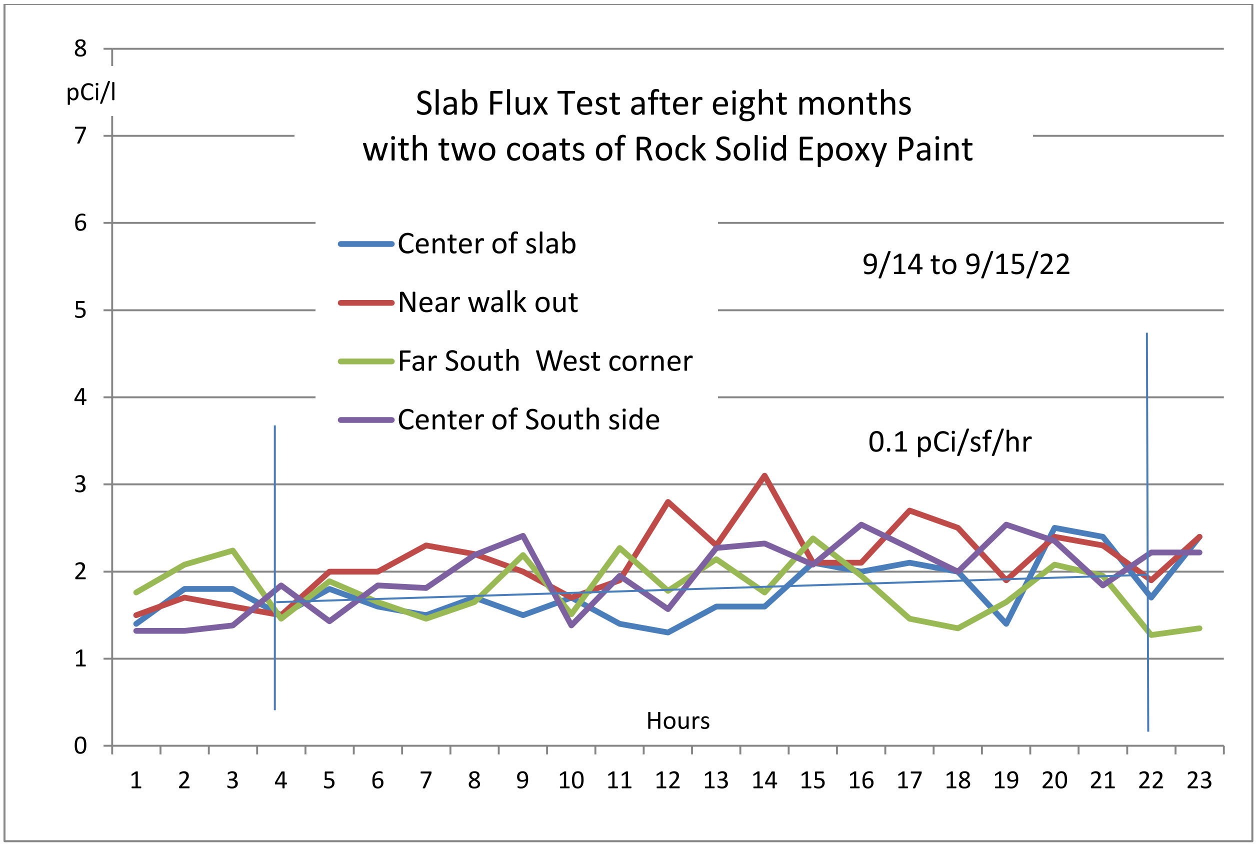

Figure (13): Flux testing slab after ten months

2.0 Measuring Indoor and Outdoor Radon Levels

2.1 Setting up the Measurements devices

Four EcoQube radon monitors, which were donated by EcoSense, were used to study the relationship between indoor radon levels and outdoor radon levels. These small radon monitors have high precision that allows measuring radon levels less than 1.0 pCi/L. They do, however, require a continuous electrical source and a connection to a Wi-Fi source. The biggest benefit for using this monitor is the data is stored continuously on a cloud system. The homeowners were given access to the cloud data so they could monitor their radon levels. The cloud storage is set up to maintain all the data until the units are cleared. This data can be downloaded later without needing to visit the home. All the hourly radon data includes the time and date so that if there is a power outage it can be accounted for. An EcoQube was placed outdoor on the upper deck inside a plastic mailbox. This location is ten feet above grade. One monitor was placed on a table in the basement and another on the first floor and a fourth on the second floor. An AcuRite weather station was mounted on a post on the upper deck. The weather station had its own solar panel to maintain its batteries and also connects to the homeowner's Wi-Fi to send data to a cloud. Although this was not the best location to monitor wind or wind direction, it provided some weather information. Unfortunately, there were often unrecorded weather data periods because the cloud storage for the weather station had a maximum 30-day storage that the author overlooked downloading in each 30-day window. The weather station would also occasionally not report any data for varying amounts of time. Both the downloaded radon and weather data needed blank rows inserted in the spreadsheet to account for missing data periods to keep date and hourly time the same for all the instruments.

2.2 Measurements results

Figure 14 indicates that the radon levels in the basement and upper floors appeared to be consistently below 4.0 pCi/L although there were basement and first floor spikes above 4.0 pCi/L. Figure 14 shows a trend of the radon levels running higher in the summer and fall months versus the spring, and winter. Figure 15 with just the basement and outdoor data shows this trend more clearly.

In Figure 14 the basement radon levels would spike to 3 to 6 pCi/L. In Figure 15, the outdoor radon levels would spike to 5 to 13 pCi/l or about double the spike levels of the basement. When the average of each level was calculated the outdoor radon level was the highest with an average of 2.73 pCi/L compared to the basement level of 2.39 pCi/L. The upper floors were consistently lower with the second floor having the lowest radon average. The patterns of outdoor radon levels higher in the summer and fall months and the lower in the winter and spring months confirms the owner's comment that he noticed the radon levels in the basement were higher in the summer months.

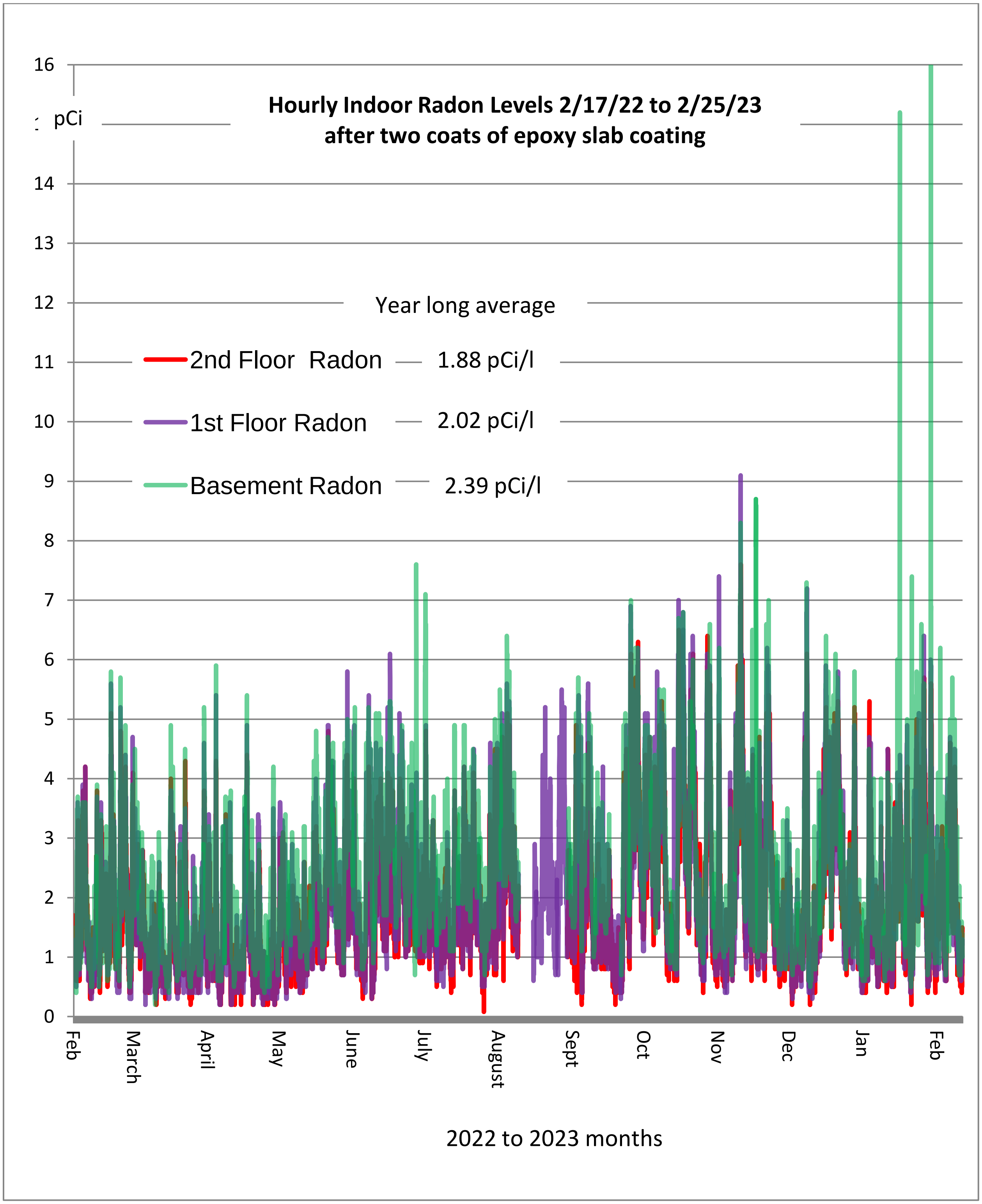

Figure (14): Indoor radon levels over 12 months

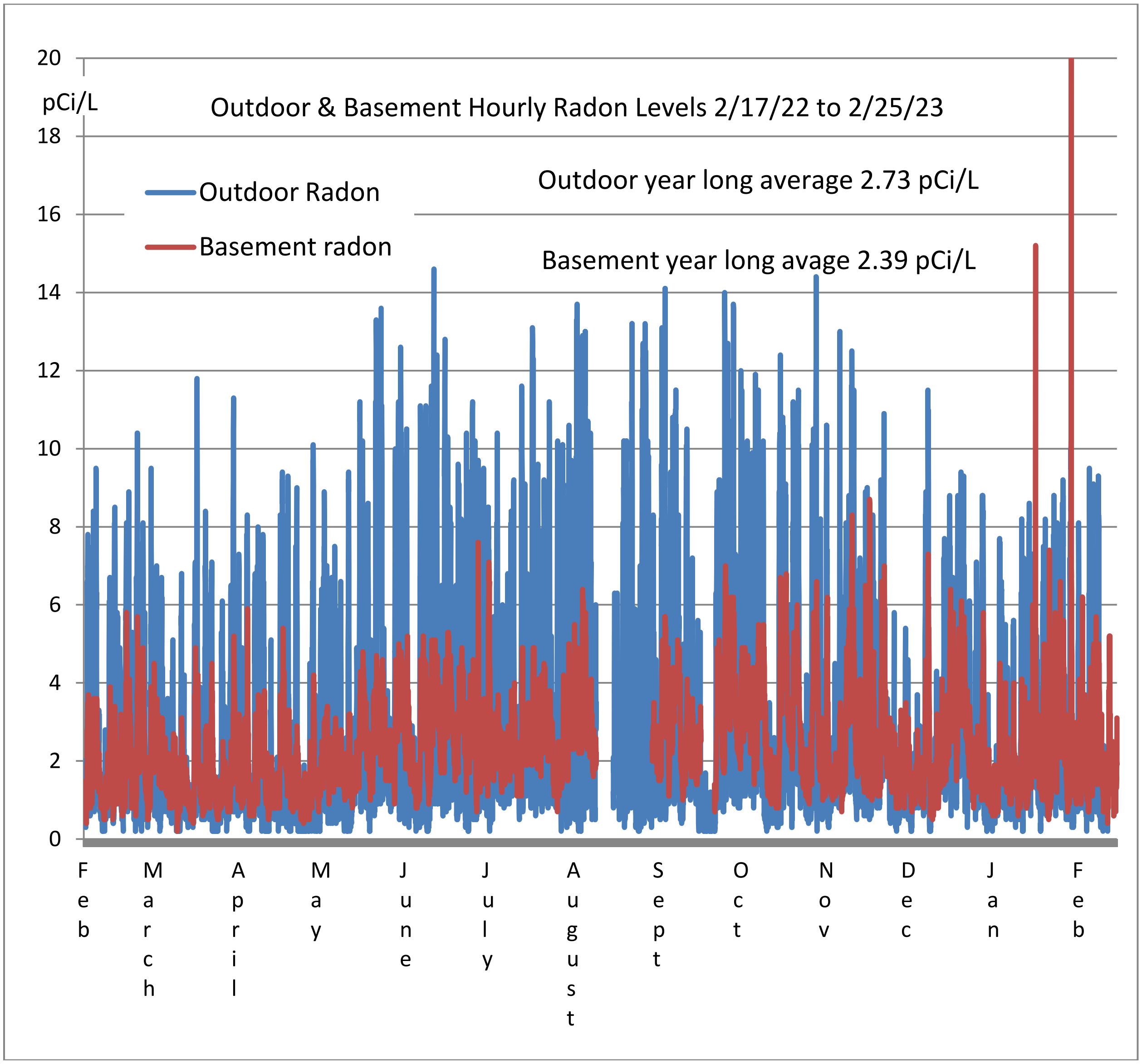

Figure (15): Outdoor radon levels compared to indoor Basement

The monthly average difference of the outdoor radon levels compared to the basement and first floor is displayed in Figure 16. This graph is not showing the actual radon monthly average but how much higher the outdoor radon levels outdoors are higher than two locations indoor. Figure 16 shows that the monthly average outdoor radon levels were greater than the green first floor level to a greater degree in the summer months than the other months. The outdoor radon monthly averages were greater than the red displayed basement averages in the fall months.

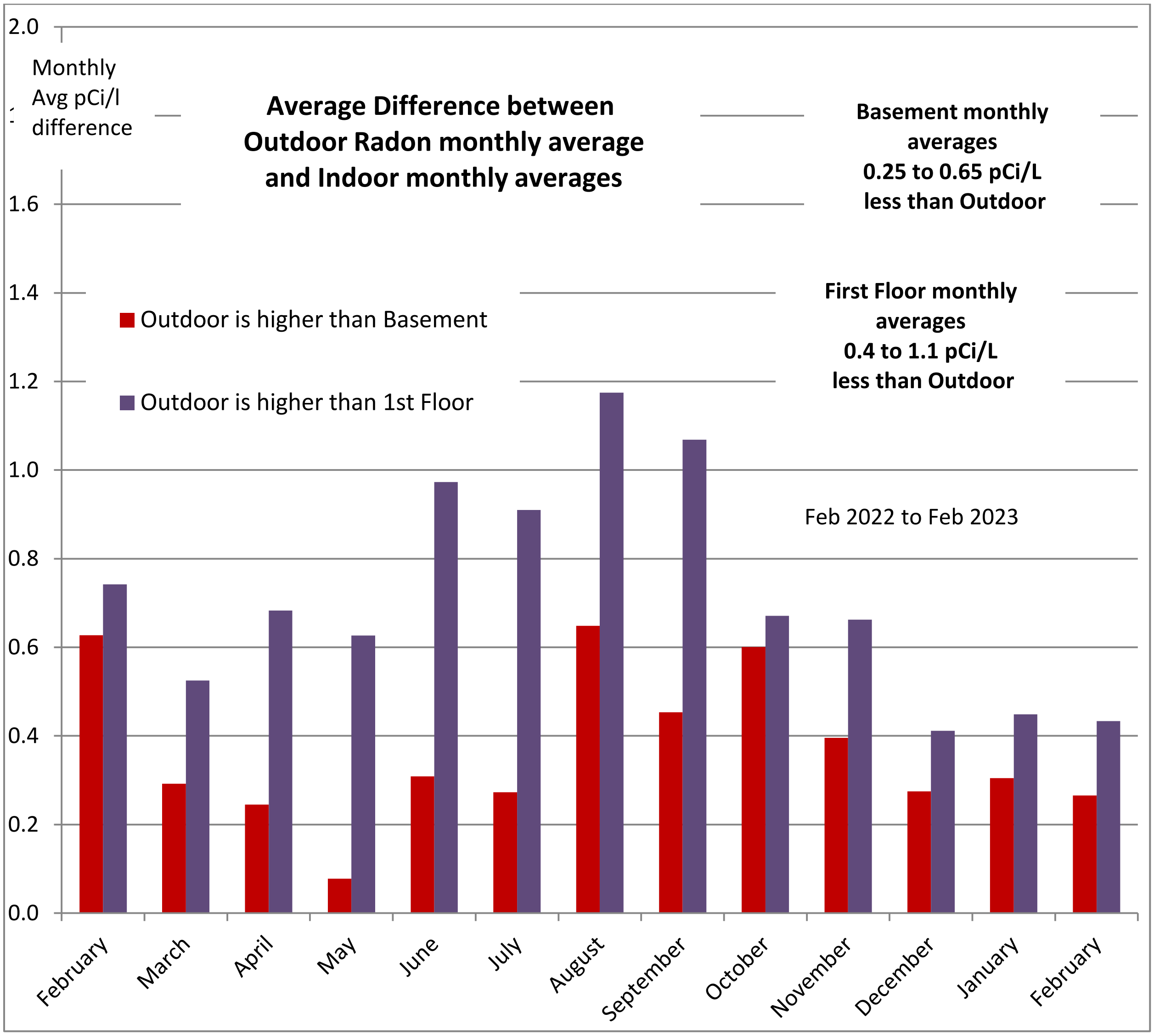

Figure (16): Comparison of outdoor to indoor monthly average radon

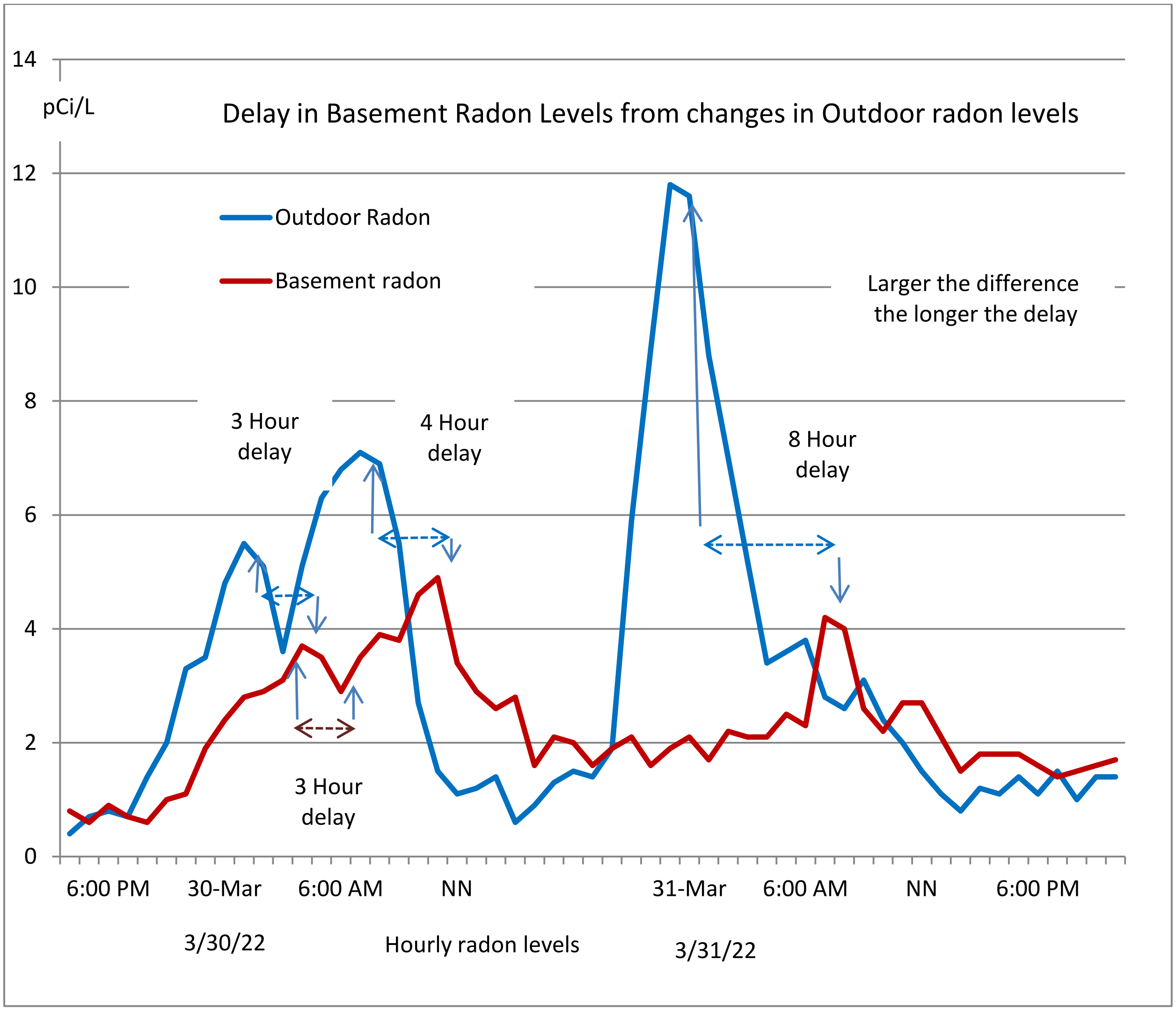

Figure (17): Delay time for outdoor radon to change indoor radon levels

Figure 17 is used to display the delay of outdoor radon levels influencing indoor radon levels. Peaks of outdoor radon appear to create peaks in indoor radon with a delay in time of three to eight hours. The delay appears to be greater when the difference between indoor and outdoor radon is greater. In general, the delay in movement of outdoor to indoor radon levels appears to be about three to four hours unless there is a large radon difference which in this case is almost 10 pCi/L. In general, the data collected appeared to indicate about a one to three hour delay in peaks of outdoor radon causing peaks in indoor radon levels. The radon levels indoors, however, did not typically fall to outdoor levels until about 4 additional hours had passed. This may be the absorption and desorption of radon into the interior building materials or some other source of radon not accounted for. Previously the air change rate of 0.15 ACH was deduced from falling radon levels. This is equivalent to the infiltration of outdoor air taking about 6.5 hours to equal the total volume of air in the basement. In general however it is assumed that multiple air changes are required to obtain equilibrium between two locations. The movement of radon into and out of building contents and materials may explain the shorter time factor between peaks compared to normal ventilation changes.

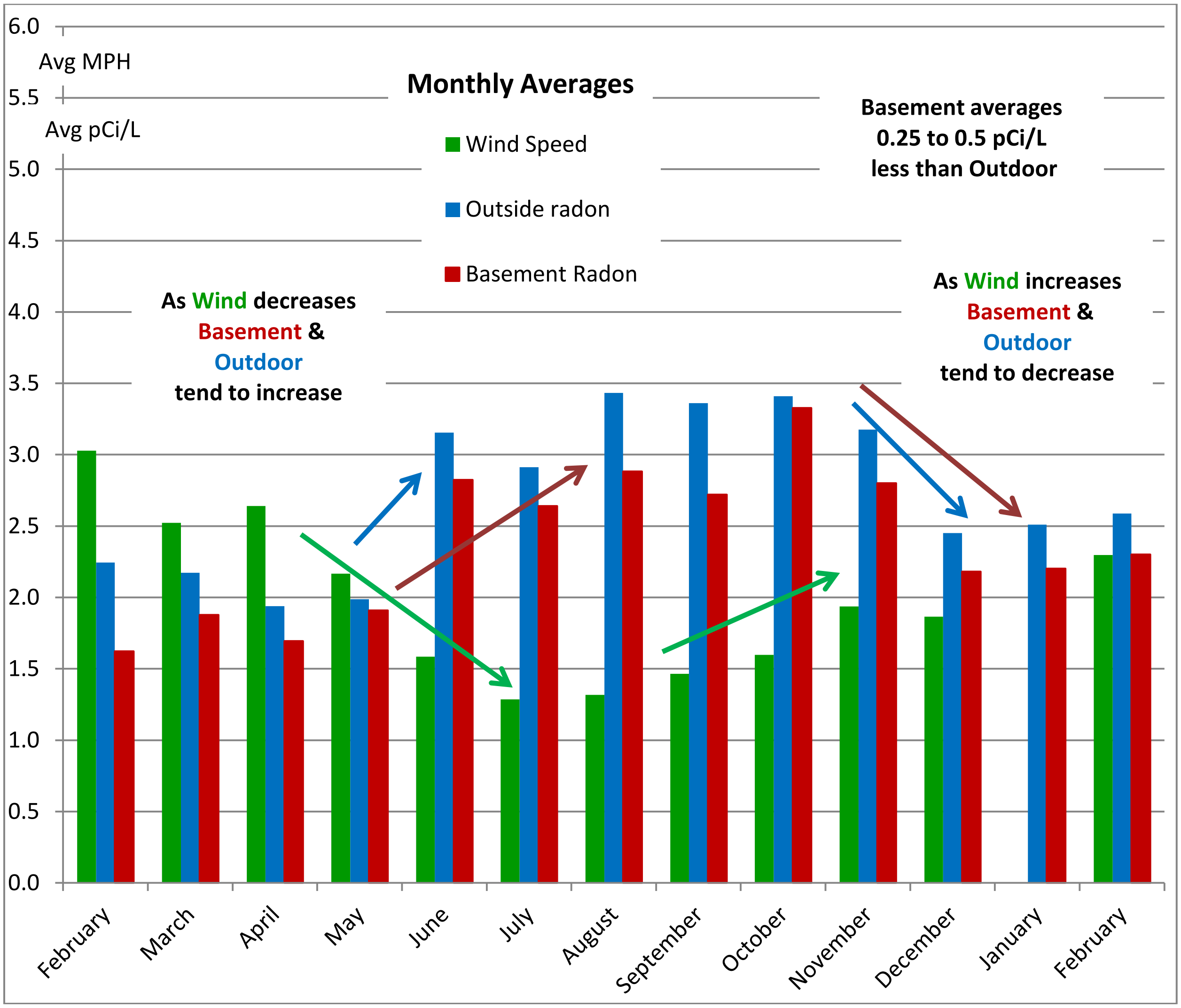

Figure (18): Average recorded wind speed on the back deck

Figure 18 depicts the monthly averages of wind speed and radon levels outdoor versus the basement indoors. The pattern of decreasing average wind and increasing average radon both outdoors and indoors can be seen in Figure 18. The relationship between the outdoor average radon levels and the indoor radon levels also had consistence throughout the months. The actual difference between the basement and the outdoor averages is consistently between 0.25 pCi/L and 0.6 pCi/L. This graph also depicts what the homeowner noticed, that the basement radon levels were higher in the summer than the winter.

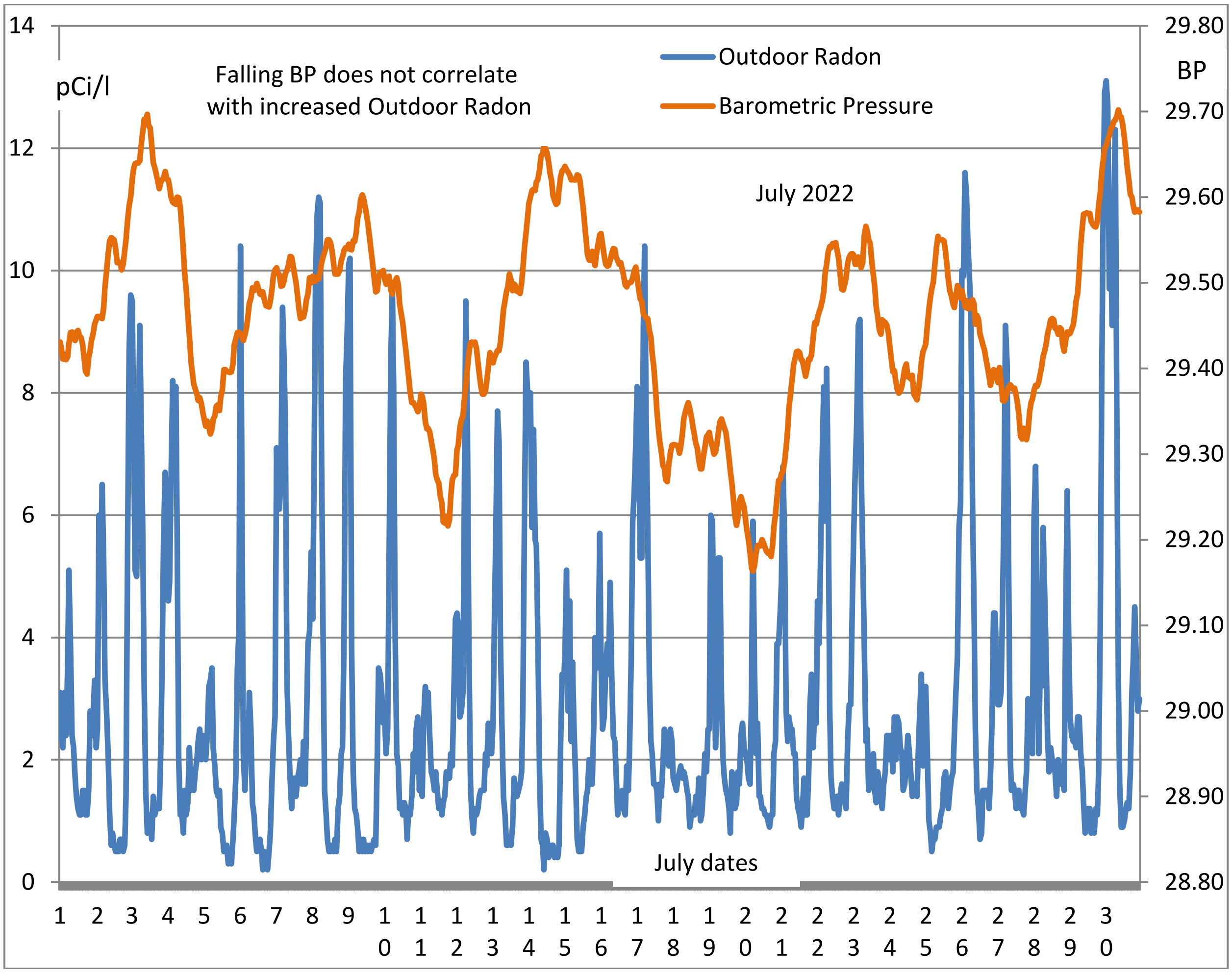

Figure (19): Comparison of barometric pressure versus outdoor radon

To determine what weather factors other than wind speed influence outdoor radon concentrations barometric pressure changes and rain fall were compared to outdoor radon level changes in Figure 19, Figure 20 and Figure 21.

It is typically assumed that when the barometric pressure is falling, radon levels in homes will be increasing as atmospheric pressure in the soil is being released to the atmosphere above the soil. To determine if dropping barometric pressure also increases outdoor radon levels, weather data for the month of July is displayed in Figure 19. July was chosen because there tends to be lower average wind speed in July. See Figure 18. In this study, the opposite was seen for four of the five periods when the barometric pressure was dropping there was no apparent increased outdoor radon. In general the strong predominance of wind or no wind influencing outdoor radon levels makes determining the influence of barometric pressure on outdoor radon levels not possible because of daytime solar gain causing air movement on a daily basis.

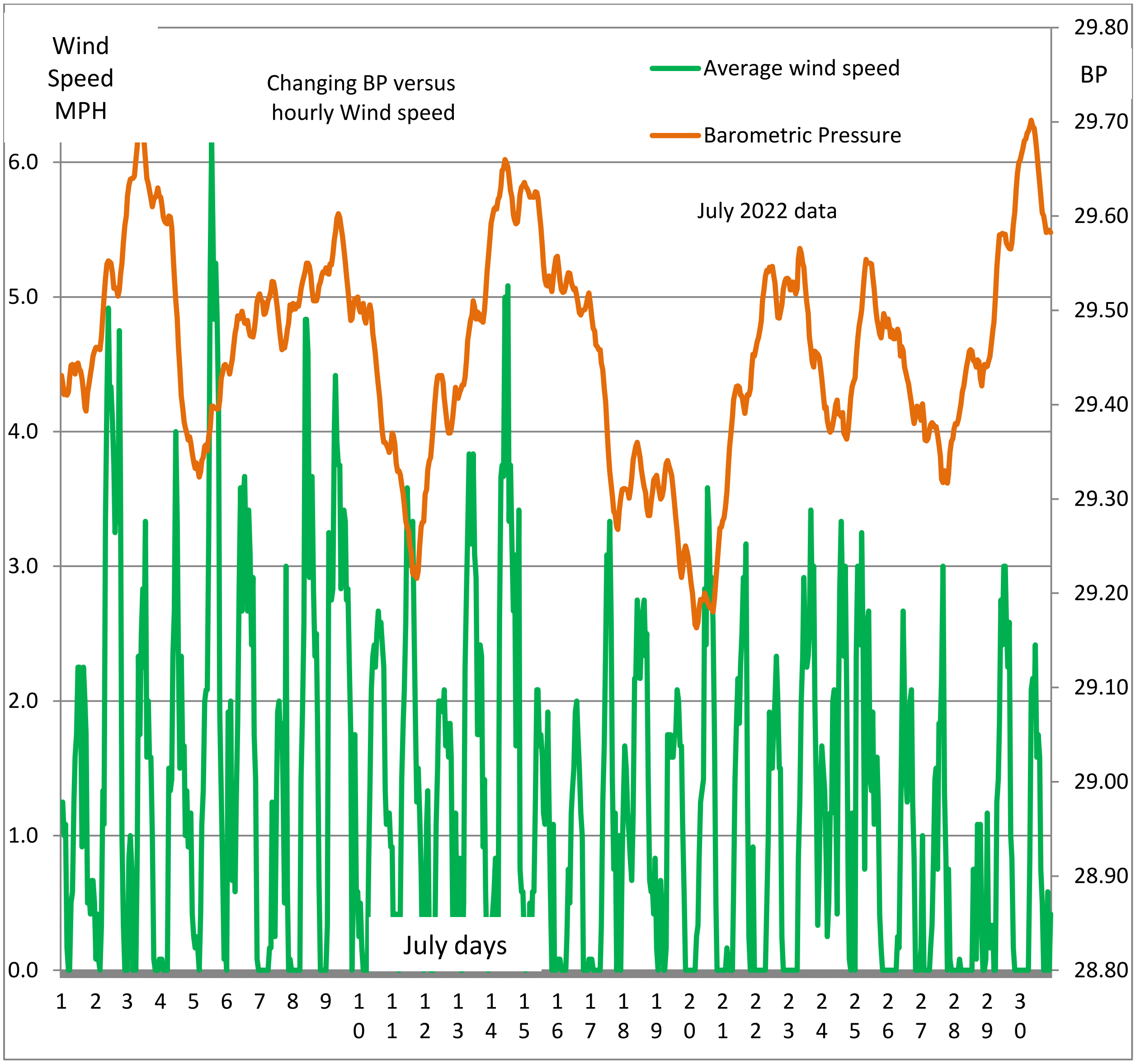

Figure (20): Comparison of Barometric Pressure versus average wind speed

Figure 20 is displayed to try and determine if the changes in barometric pressure was related to changes in wind speed. In Figure 20, the average hourly wind speed in the month of July was compared to rising and falling barometric pressure. There does not appear to be a connection between the wind speed and barometric pressure. Weather influences other than barometric pressure appear to be causing changes and intensity of wind speed. Without multiple days of no wind, the influence of barometric pressure change on outdoor radon levels cannot be determined.

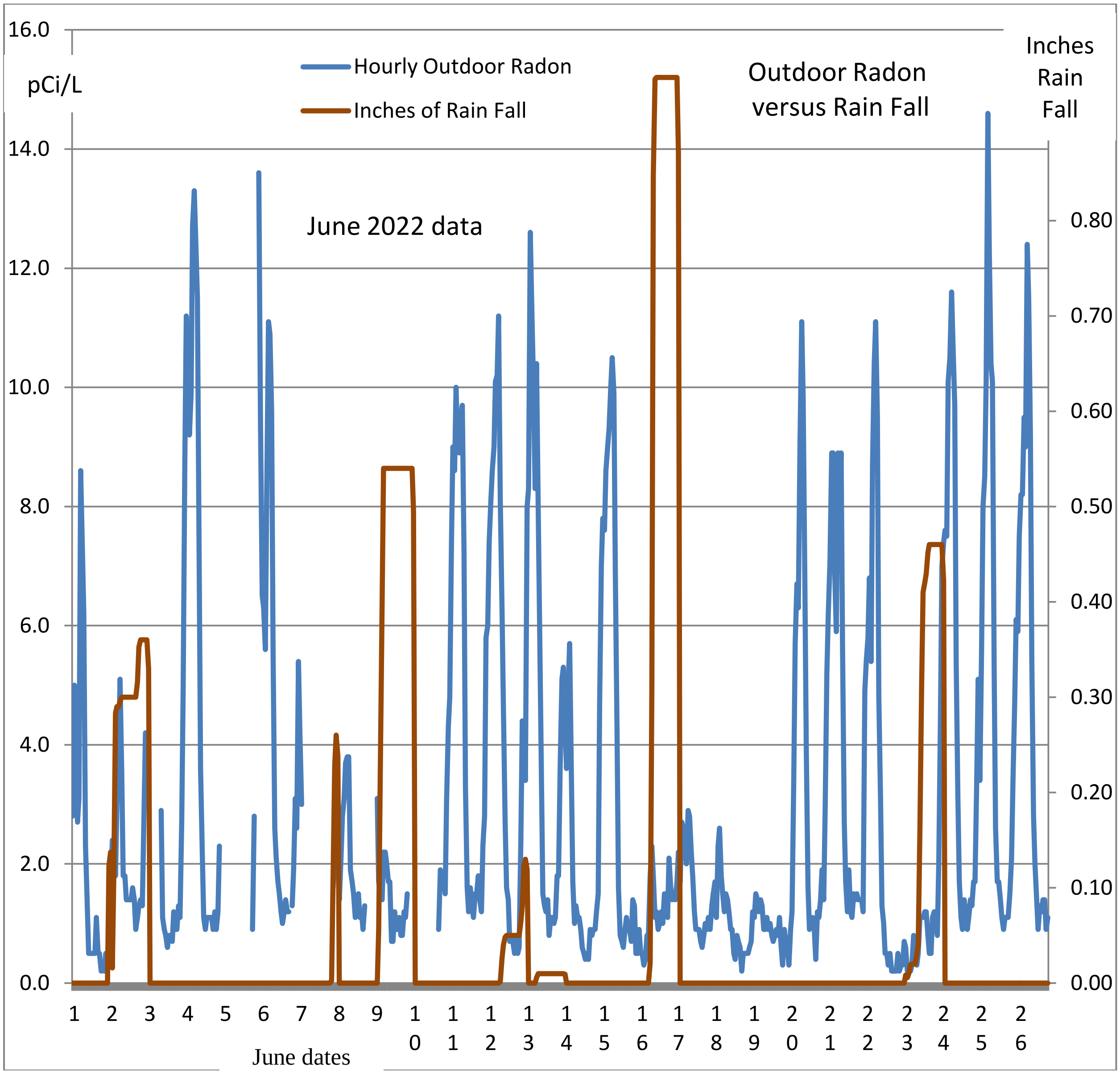

Figure (21): Comparison outdoor radon versus rainfall

Rainfall is often correlated with increased radon levels indoors due to soil moisture capping or water movement down into the soil pushing radon into a home. Figure 21 is used to display periods of rainfall in the month of June and the changes in outdoor radon levels. In June of 2022 outdoor rain predominately happened when the outdoor radon levels were low which might indicate capping of the soil, reducing radon movement up into the atmosphere. If this was occurring the containment of radon would likely cause elevated outdoor radon when the soil moisture had depleted which is not consistent in this data. Overall the data does not show a correlation between rainfall and outdoor radon levels.

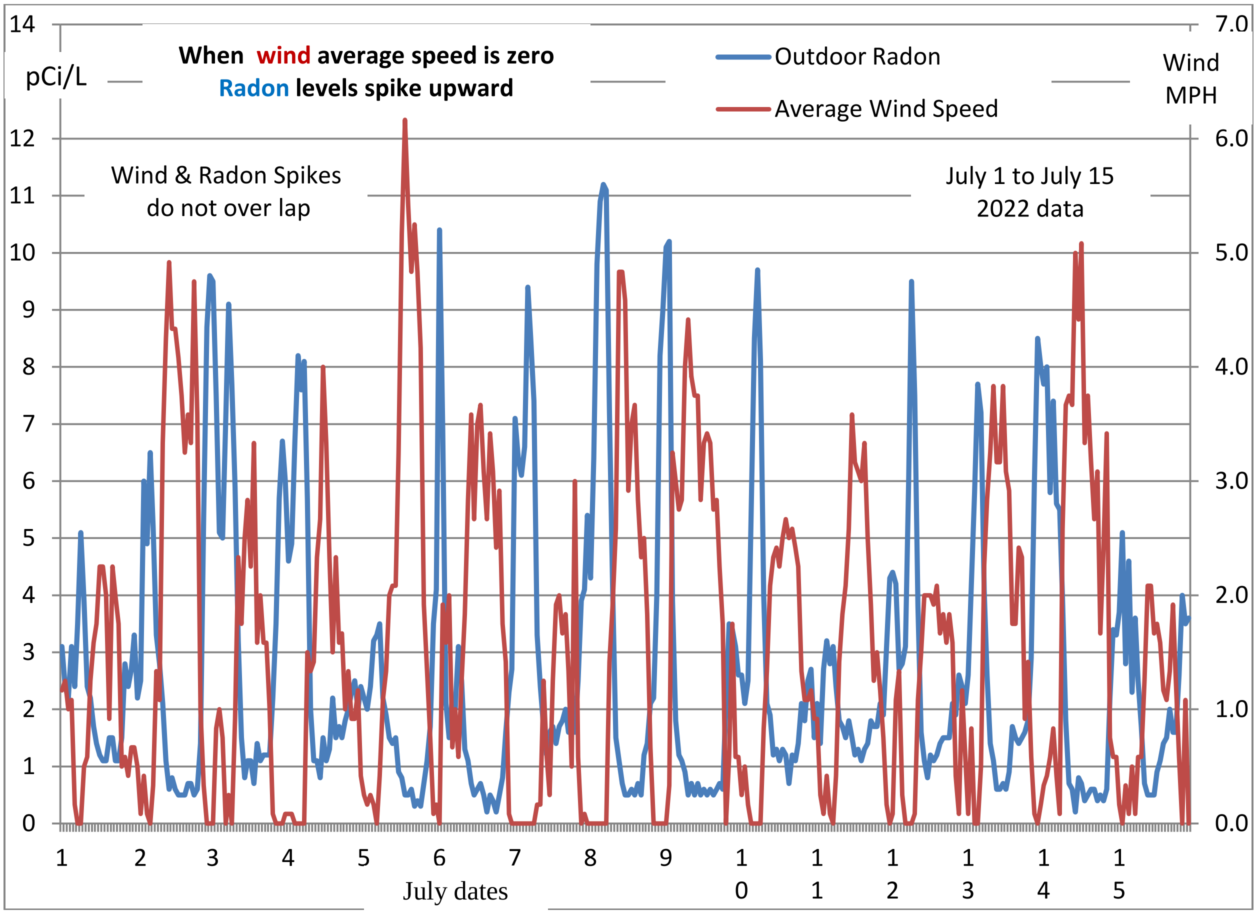

Figure (22): Comparison outdoor radon versus wind

In Figure 22 the average hourly wind speed in red is plotted against hourly outdoor radon levels in blue. The wind speed recorder was located on the outer hand rail of the main floor rear deck of the study house. See Figure 7 with a picture of the rear deck.

Note that the spikes in Figure 22 do not overlap. The graph is easier to follow by viewing individual spikes. When the red wind speed line sits on the bottom of the graph, the wind speed is at zero MPH and the blue outdoor radon line spikes upward. When the blue radon line hovers around 1 pCi/L, the red wind speed average is spiking higher. This clearly shows the dominant relationship between outdoor radon levels and wind speed.

2.3 Post Project Radon Monitor Spiking

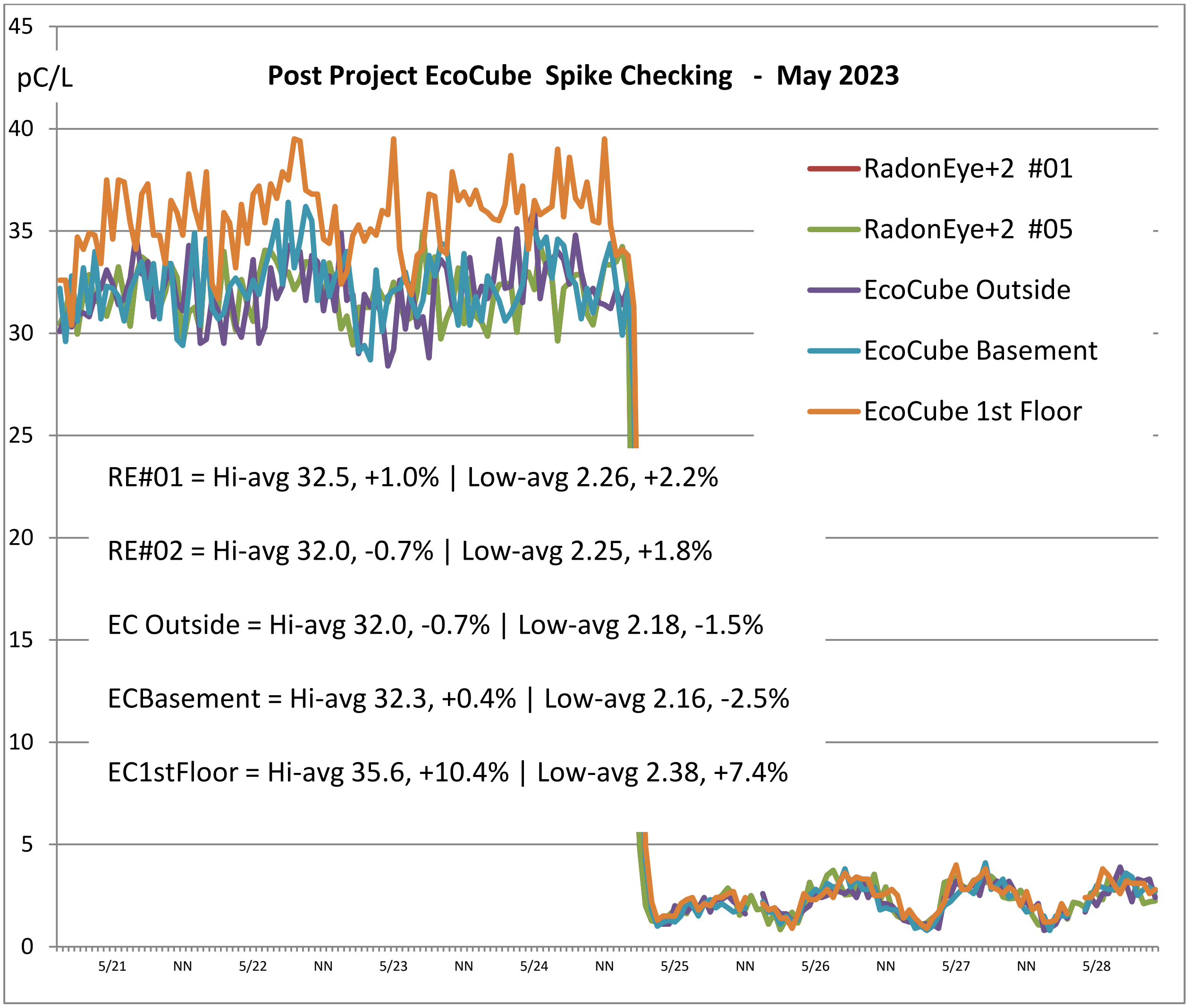

Figure (23): Chamber comparison of Radon Monitor

In order to check if the radon monitors had significant bias from each other by the end of the study, the three remaining working EcoCubes were placed in the author's radon chamber and exposed for four days of elevated radon levels and four days of low level radon levels. Figure 23 displays the results of this testing in comparison with two RadonEye monitors that had been calibrated based on Bowser Morner chamber spiking in 2021. The percentages given in Figure 23 are a comparison between the overall average of all of the spiked monitors except the first floor monitor which showed a 7 to 10 percent high bias during this spiking. The basement and outdoor EcoCubes were within a few percentage points of each other. If the first floor radon monitors low radon level bias of about plus 7% was used to correct the first floor year long average of 2.02 pCi/L, the new result would be 1.88 pCi/L average which is exactly what the second floor year long average was.

3.0 Conclusions from the study

The stopping of infiltrating sub-slab radon using sub-slab depressurization has long been shown to be the primary way to successfully reduce radon levels below the action level. Many homes also require depressurizing the adjacent to the basement slabs such as an attached garage or front concrete porch to further reduce indoor radon levels. The radon levels in this study house were coming from infiltration of soil gas from these locations but they were also coming from radon fluxing through the slab and outdoor radon moving indoors. As clients ask for radon levels to be mitigated lower than the action level, it will be necessary to consider radon flux and outdoor radon sources, especially as homes are built more airtight and mechanical outdoor air ventilation is not installed. The lower ventilation rate of newer homes increases the influence of smaller sources of radon as would be expected from concrete flux or even outdoor radon levels. This study showed that radon fluxing from or through concrete can be an important considerations to achieving the goal of having indoor radon levels approach outdoor radon levels, especially in areas with very high sub-slab radon levels. Future studies should continue to examine the influence of radon flux in air tight homes. This study showed that epoxy coatings can stop radon flux coming out of or through a slab. The study showed that outdoor radon levels were predominately correlated with wind speed and that outdoor readings at ten feet above grade were similar to readings at two feet. In areas with very high soil radon levels, indoor ventilation using outdoor air may need to take into consideration coordinating the ventilation run time with periods of outdoor wind to utilize lower outdoor radon levels.

4.0 Reference Papers

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2) Brodhead B., Measuring At-Grade Radon Mitigation Exhaust,
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5) Brodhead B., Measuring radon and thoron emanation from concrete and granite with continuous radon monitors and E-PERMs. Proceedings of AARST International Radon Conference; 2008

6) Brodhead B. Brennan T, Clarkin M., Initial results from Follow-up of New Jersey homes mitigated for radon, Proceedings of AARST International Radon Conference; 1993