PROCEEDINGS OF THE 2015 AARST INTERNATIONAL RADON SYMPOSIUM

September 20 –September 23, 2015
Bloomington, Minnesota

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RELATIVE RESPONSES OF BARE AND ENCLOSED CR-39 ALPHA-TRACK DETECTORS UNDER CONDITIONS OF HIGH AND LOW PARTICLE CONCENTRATION

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Abstract

Six bare CR-39 detectors were placed in contact with filters that had been used to make grab radon progeny measurements from the Bowser-Morner radon chamber; the number of filters per detector ranging from 1 to 6. The net track density on these detectors increased as a function of the number of filters with which they were in contact. This provided compelling evidence that alpha particles emitted from radon progeny on the surface of CR-39 produce observable tracks in that material. Deposition of radon progeny on surfaces, including bare alpha-track detectors, should be greater when the particle concentration in the air is small than when it is large. A study was conducted to determine how particle concentration would affect the relative responses of bare and enclosed CR-39 alpha-track detectors in the Bowser-Morner radon chamber. Forty bare CR-39 alpha-track detectors and ten enclosed detectors of the same type were exposed in the Bowser-Morner chamber for twenty days with a very low particle concentration and thus low equilibrium of radon progeny. Another set of forty bare detectors and ten enclosed detectors was exposed for fifteen days with particles added to the air to create an equilibrium condition of about 60%. In the latter case, the resulting track densities observed on the bare detectors averaged a factor of 1.99 greater than the track densities observed on the enclosed detectors. In the former case with a very low particle concentration, the average track density on the bare detectors was significantly greater, averaging 3.35 times that of the enclosed detectors. The response of the bare detectors at low equilibrium was found to be 69% greater than at a higher equilibrium. The results of the study provide evidence of the following: 1) alpha particles emitted from radon progeny on the surface of CR-39 produce observable tracks, 2) when the particle concentration in the air is small, radon progeny deposit more on surfaces than when the particle concentration is high and 3) the response of bare CR-39 alpha-track detectors is highly dependent upon the concentration of particles in the air.

Introduction

Previous studies (for example, George, et al., 1983) have shown that radon progeny require particles on which to attach in order to stay suspended in air. When the particle concentration in the air is low, radon progeny migrate to, and deposit on, whatever surfaces are available, thus lowering their concentration in the air and lowering their equilibrium with the parent radon in the air. That being the case, bare plastic material used to measure alpha particles by etching to form tracks should also have more radon progeny deposited on them when the particle concentration in the air is low than when it is high and would thus have a higher track density provided that alpha particles emitted from radon progeny on the surface of the detector produce observable tracks. However, some plastic materials, such as cellulose nitrate (LR-115) have a high linear energy transfer (LET) threshold for the formation of tracks, and therefore alpha particles emitted from radon progeny deposited on the surface are too energetic to produce tracks until they have lost energy by passing through a portion of the plastic. In other words, etching the surface would not detect tracks in cellulose nitrate from alpha particles emitted from radon progeny deposited on the surface. However, allyl diglycol carbonate (CR-39) has a much lower LET threshold for the formation of tracks. One reference (Ng et al., 2007) states that CR-39 has no "relevant threshold" energy for alpha particles for the formation of tracks. In other words, alpha particles emitted from radon progeny, even though at a relatively high energy, should produce tracks from the surface of CR-39.

In an undocumented previous study, bare alpha-track detectors and enclosed detectors of the same type were exposed simultaneously in Bowser-Morner's radon chamber. The results of that exposure showed that the track densities on the bare detectors were significantly greater than on the enclosed detectors. This was an indication that alpha particles emitted by radon progeny that had deposited on the surface of the bare detectors produced observable tracks. This preliminary study was done with no particles introduced into the chamber air, and thus at a low equilibrium. The authors wished to conduct a more detailed study 1) to verify that alpha particles emitted from radon progeny on the surface of CR-39 produce observable tracks and 2) to observe the effect that two very different particle concentrations in the Bowser-Morner chamber would have on the deposition of radon progeny and thus the relative response of bare and enclosed CR-39 detectors. Also of interest was any effect that orientation of bare detectors inside the chamber might have.

Method

In order to verify that alpha particles emitted from radon progeny on the surface of CR-39 produce observable tracks, bare CR-39 detectors were placed in contact with filters that had been used for grab radon progeny measurements from the Bowser-Morner chamber. After each grab measurement was analyzed for radon progeny concentration, a bare CR-39 detector was placed in contact with the filter and left there overnight; long enough for all of the radon progeny to decay. Six bare detectors were exposed in this manner, one to one filter, one to two filters, etc. with the maximum being six filters. These detectors were sent to the manufacturer's laboratory for analysis along with four bare detectors as blanks.

To measure the relative response of bare and enclosed CR-39 detectors, forty bare CR-39 alpha-track detectors were randomly assigned, eight each to the top and four sides of a cardboard box. Ten enclosed alpha-track detectors of the same type were also randomly assigned, two each to the same surfaces of the box. The box was placed inside the Bowser-Morner radon chamber, as shown in Figure (1), about 1.2 m (4 ft) from the chamber door. The detectors were exposed for a period of twenty days. During this period, no particles were injected into the chamber air, so the particle concentration in the air was very low. No particle counter was used, and no measurements of radon progeny were made during this period. However, in the past, with these same conditions, the particle concentration in the chamber was measured to be less than 50 per cm^3, and the radon progeny equilibrium was measured to be about 5%. After the exposure period, the detectors were sent to the manufacturer's laboratory for processing along with ten bare detectors and three enclosed detectors as blanks.

Figure (1): Box with bare and enclosed detectors placed inside chamber

The entire exposure was repeated as stated above, this time with a particle generator injecting an aerosol of sodium chloride particles into the chamber air. Again, no particle counter was used, but in the past with this condition the particle concentration was measured to be greater than 10^4 particles per cm^3. The radon decay product equilibrium was measured to be approximately 60%. The detectors were exposed for a period of fifteen days. The detectors were sent to the manufacturer's laboratory for processing along with nine bare detectors and two enclosed detectors as blanks.

Results

The results of the six bare detectors that were placed in contact with filters used to make radon progeny grab measurements are presented in Table 1. The average blank track density, 0.56 tracks/mm^2, was subtracted from each of the reported track densities for these detectors; the individual blank values were 0.46, 0.54, 0.57, & 0.65 tracks/mm^2. These results are shown graphically in Figure (2).

Table 1. Net track density (tracks/mm^2), bare detectors, exposed to indicated number of filters

1	2	3	4	5	6
19.48	39.88	55.15	70.49	81.81	85.62

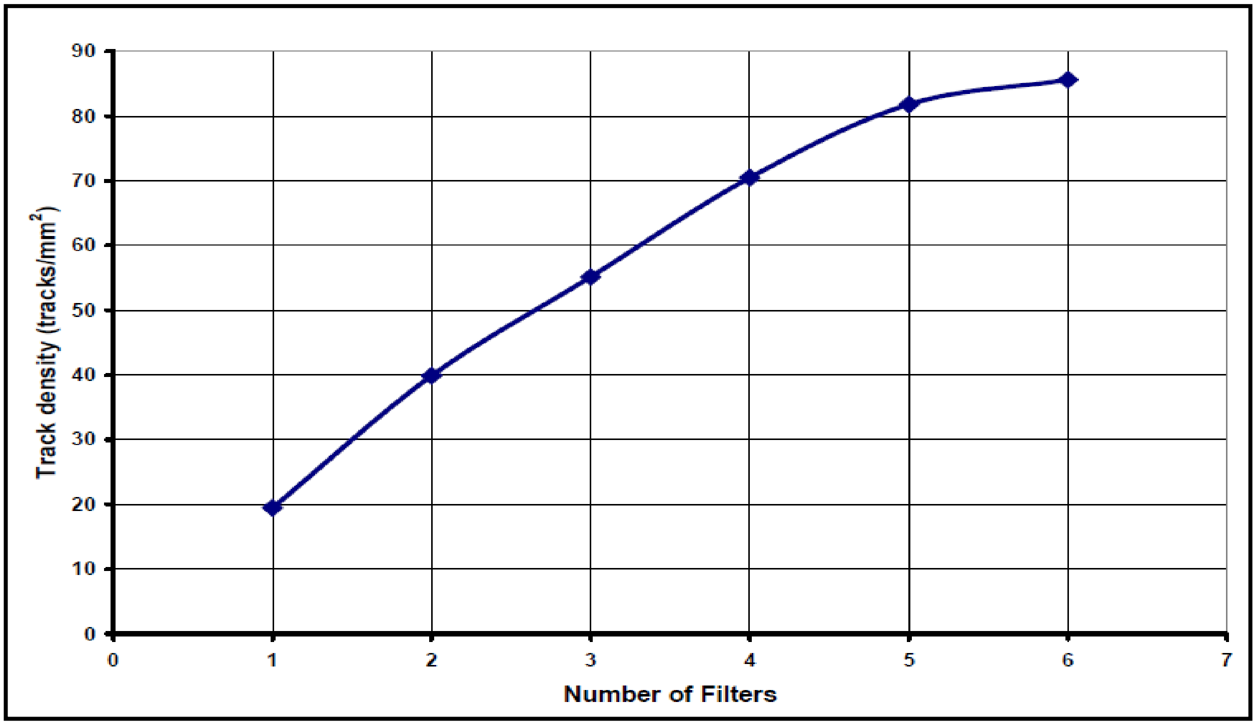

Figure (2): Net track density as a function of number of filters to which the detector was exposed.

The results from the first set of bare detectors exposed in the Bowser-Morner chamber when no particles were added to the chamber air are presented in Table 2 in terms of net track density in tracks/mm^2. The average blank track density, 0.34 tracks/mm^2, was subtracted from each of the reported track densities; the individual blank values were, 0.26, 0.28, 0.31, 0.31, 0.31, 0.32, 0.34, 0.34, 0.35, & 0.57 tracks/mm^2. In Table 2, the surfaces of the box are labeled A through E, as shown in Figure (3), with A being the top of the box and B facing the chamber door. The Positions 1 – 8 are the order in which the detectors were placed on the surface; for Surfaces B – E Position 1 is the top detector and Position 8 is the bottom detector and for Surface A, Position 1 is farthest from the chamber door and Position 8 is closest to the door. A statistical analysis indicated that there was no significant effect due to Position, so the data were analyzed using a one-way Analysis of Variance (ANOVA) with Surface being the only independent variable. This analysis indicated a significant effect due to Surface. In other words, the track density was affected by the orientation of the bare detectors in the chamber. Although this effect was statistically significant, the largest difference in average net track density between two surfaces was only 8.4%. The net track density averaged over all forty detectors was 76.69 ± 3.56 tracks/mm^2 (unless otherwise stated, average values are reported with ± one standard deviation).

The results from the first set of enclosed detectors when there was a low particle concentration in the chamber air are presented in Table 3 in terms of net track density. In Table 3, the variables Surface and Position are defined in the same manner as in Table 2, just with fewer detectors. The average track density for the enclosed blanks was 0.46 tracks/mm^2; the individual blank values were 0.47, 0.48 & 0.43 tracks/mm^2. A statistical analysis again indicated that there was no effect due to Position. A one-way ANOVA indicated that there also was no effect due to

Surface. In other words, the orientation of these detectors had no significant effect on their response, as was expected since they were enclosed with filtered openings and should not have been affected by radon progeny outside of the enclosure. The net track density averaged over all ten enclosed detectors was 22.86 ± 0.88 tracks/mm^2. The relative response of the bare detectors to the enclosed detectors was therefore (76.69 ± 3.56)/(22.86 ± 0.88), or a factor of 3.35 ± 0.20.

Table 2. Net track density (tracks/mm^2), bare detectors, low particle concentration

Position	A	B	C	D	E
1	70.60	83.56	77.88	76.49	83.57
2	74.01	82.45	77.25	74.53	82.67
3	75.11	79.34	68.08	74.21	81.12
4	76.41	79.74	76.24	73.89	78.61
5	76.59	77.44	77.44	71.86	77.97
6	75.89	77.70	75.90	73.19	77.04
7	76.72	77.80	74.38	74.18	79.79
8	70.88	80.61	73.73	72.69	80.22
Average	74.53	79.83	75.11	73.88	80.12
Std Dev	2.50	2.27	3.19	1.38	2.27

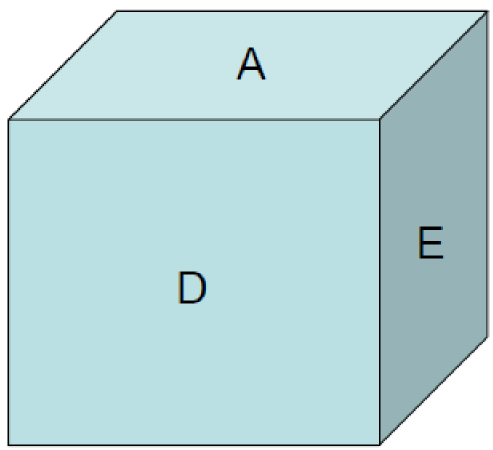

Figure (3): Relative positions of the surfaces

Table 3. Net track density (tracks/mm^2), enclosed detectors, low particle concentration

Position	A	B	C	D	E
1	23.14	22.12	21.65	23.66	22.89
2	23.51	22.42	24.23	23.37	21.60
Average	23.32	22.27	22.94	23.52	22.25
Std Dev	0.26	0.21	1.82	0.21	0.91

The average net track densities for the bare and enclosed detectors for the first exposure are shown graphically in Figure (4). In that figure, the error bar on each column is ± two times the standard deviation around the average net track density.

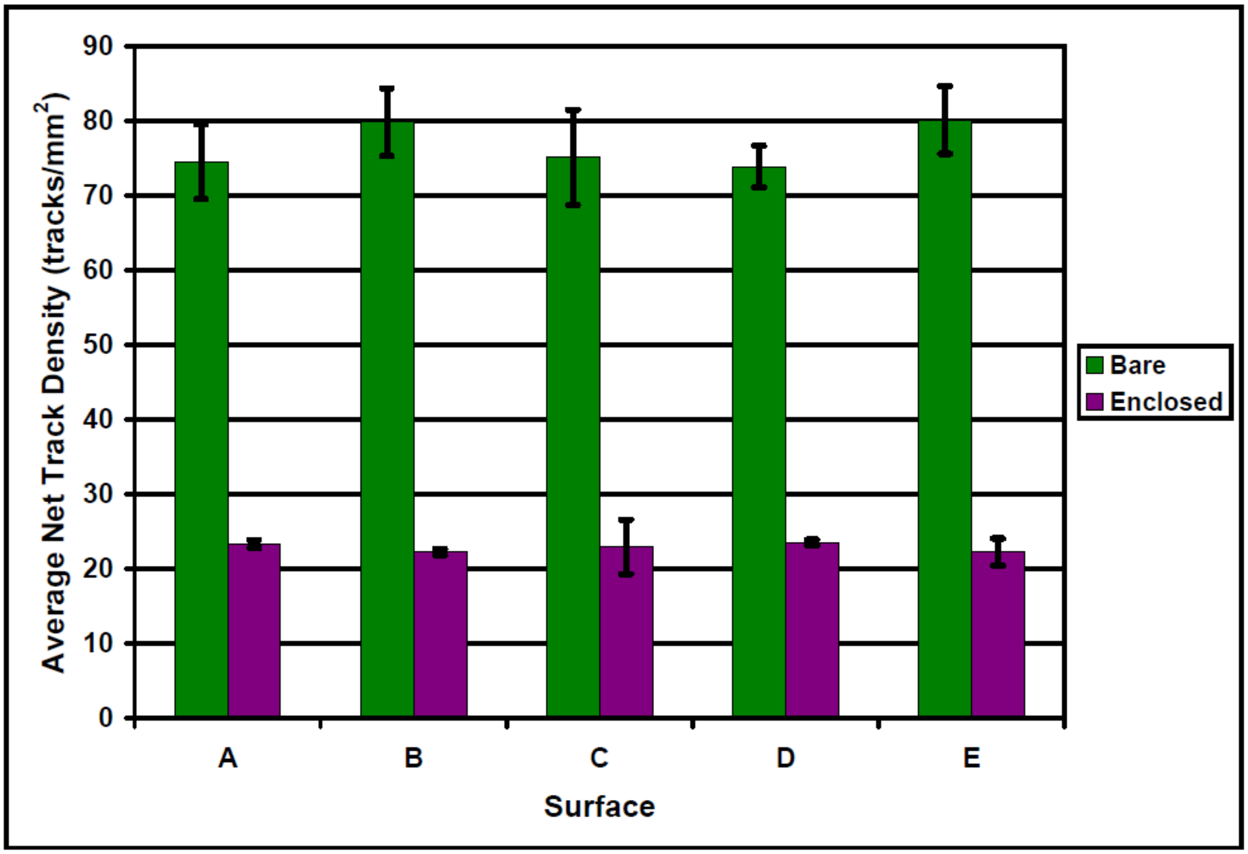

Figure (4): Average net track densities with low particle concentration

The results from the second set of bare detectors when particles were added to the chamber air are presented in Table 4 in terms of net track density in tracks/mm^2. The average blank track density, 0.26 tracks/mm^2, was subtracted from each of the reported track densities for the exposed detectors; the individual blank values were 0.11, 0.17, 0.19, 0.19, 0.22, 0.27, 0.33, 0.37, & 0.46 tracks/mm^2. In Table 4, the surfaces and positions are as described above for Table 2. Unfortunately, the laboratory indicated that the surfaces of nine of the forty bare detectors were damaged and therefore the reported values of track density should be ignored. Although several of these values were very close to the average track density for the others on the same surface, they were excluded from any of the analyses, as indicated in Table 4. A statistical analysis indicated that there was no significant effect due to Position, so the data were analyzed using a one-way ANOVA with Surface being the only independent variable. This analysis indicated a significant effect due to Surface. In other words, the track density was affected by the orientation of the bare detectors. Although this effect was statistically significant, the largest difference in average net track density between two surfaces was only 5.7%. The net track density averaged over the 31 detectors was 33.94 ± 1.61 tracks/mm^2.

Table 4. Net track density (tracks/mm^2), bare detectors, high particle concentration

Position	A	B	C	D	E
1	33.92	34.19	*	32.02	35.19
2	34.73	31.52	33.61	*	36.15
3	*	33.25	33.87	31.51	*
4	37.28	*	34.90	*	*
5	35.04	*	34.57	32.85	33.95
6	35.23	30.04	34.47	32.15	34.66
7	36.53	32.71	*	32.48	34.27
8	35.64	33.77	33.70	32.33	35.53
Average	35.48	32.58	34.18	32.23	34.96
Std Dev	1.13	1.55	0.53	0.45	0.82

* Damaged detector, measurement excluded.

The results from the second set of enclosed detectors when there was a high particle concentration in the chamber air are presented in Table 5 in terms of net track density. In Table 5, the surfaces and positions are as described above for Table 3. The average track density for the enclosed blanks was 0.71 tracks/mm^2; the individual blank values were 0.69, & 0.73 tracks/mm^2. A statistical analysis again indicated there was no effect due to Position. A one-way ANOVA indicated that there also was no effect due to Surface. In other words, the orientation of the enclosed detectors had no significant effect on the response of the detectors, as in the first exposure. The net track density averaged over all ten enclosed detectors was 17.05 ± 1.00 tracks/mm^2. The relative response of the bare detectors to the enclosed detectors was therefore (33.94 ± 1.61)/(17.05 ± 1.00), or a factor of 1.99 ± 0.15.

Table 5. Net track density (tracks/mm^2), enclosed detectors, high particle concentration

Position	A	B	C	D	E
1	17.63	17.08	16.59	17.17	16.42
2	18.67	14.87	17.74	17.00	17.39
Average	18.15	15.97	17.17	17.08	16.90
Std Dev	0.74	1.56	0.81	0.13	0.69

The average net track densities for the bare and enclosed detectors for the second exposure are shown graphically in Figure (5). In that figure, the error bar on each column is ± two times the standard deviation around the average net track density.

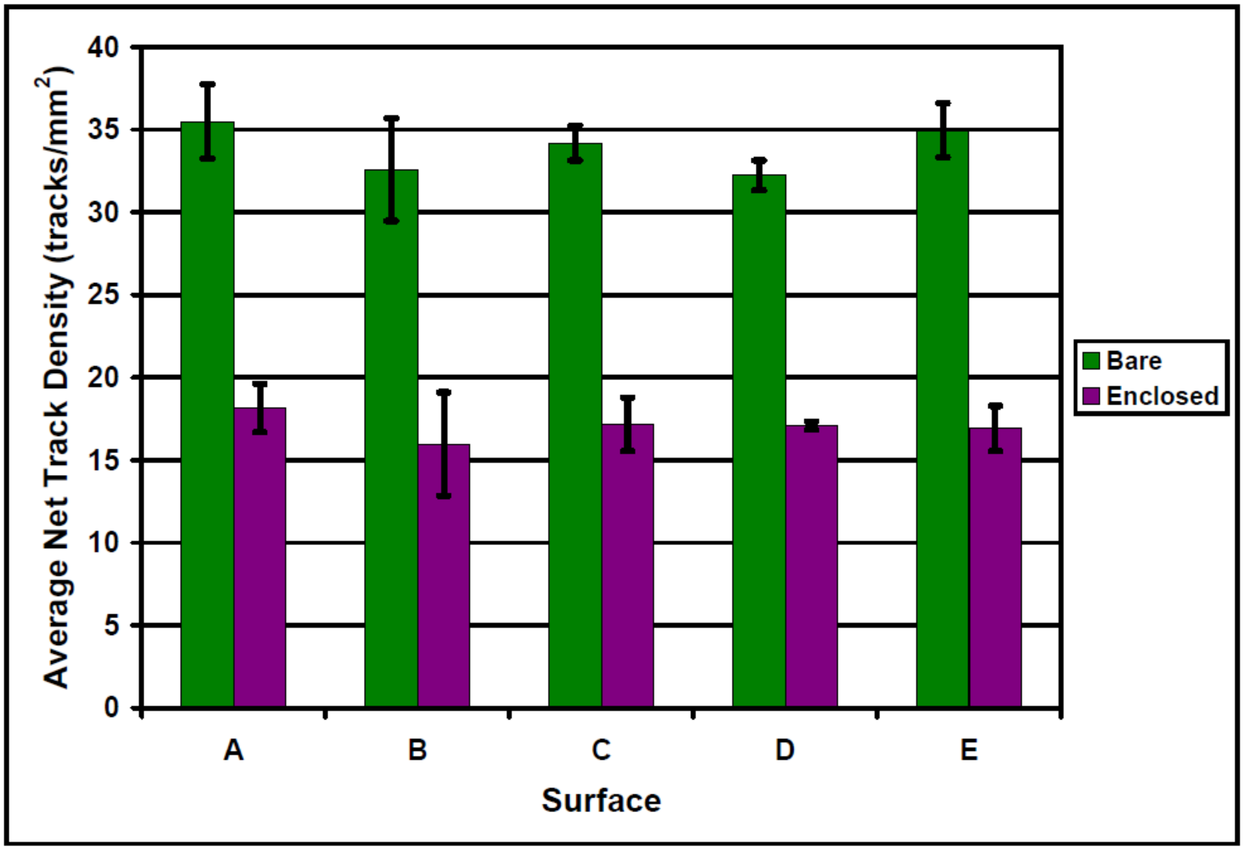

Figure (5): Average net track densities with high particle concentration

Discussion

The results shown in Table 1 and Figure (1) indicate a definite trend of increasing track density with the number of filters to which the detectors were exposed. This is a clear indication that alpha particles emitted by radon progeny on the surface of the detectors do indeed result in observable tracks in the CR-39 material. The leveling off of track density with increasing number of filters, obvious in Figure (1), was due to a combination of two factors; 1) the detectors in contact with 4, 5 and 6 filters were each in contact with one filter that had a slightly less activity of radon progeny on it compared to all the other filters and 2) with increasing track density some tracks are lost in the counting process due to overlapping. This can be seen in Figure (6) where with increased track density some pairs or groups of overlapping tracks would be counted as only one track. If the track density values had been converted to exposure in Bq-hours/m^3 (pCi-days/liter), an algorithm would have been applied to correct for this loss.

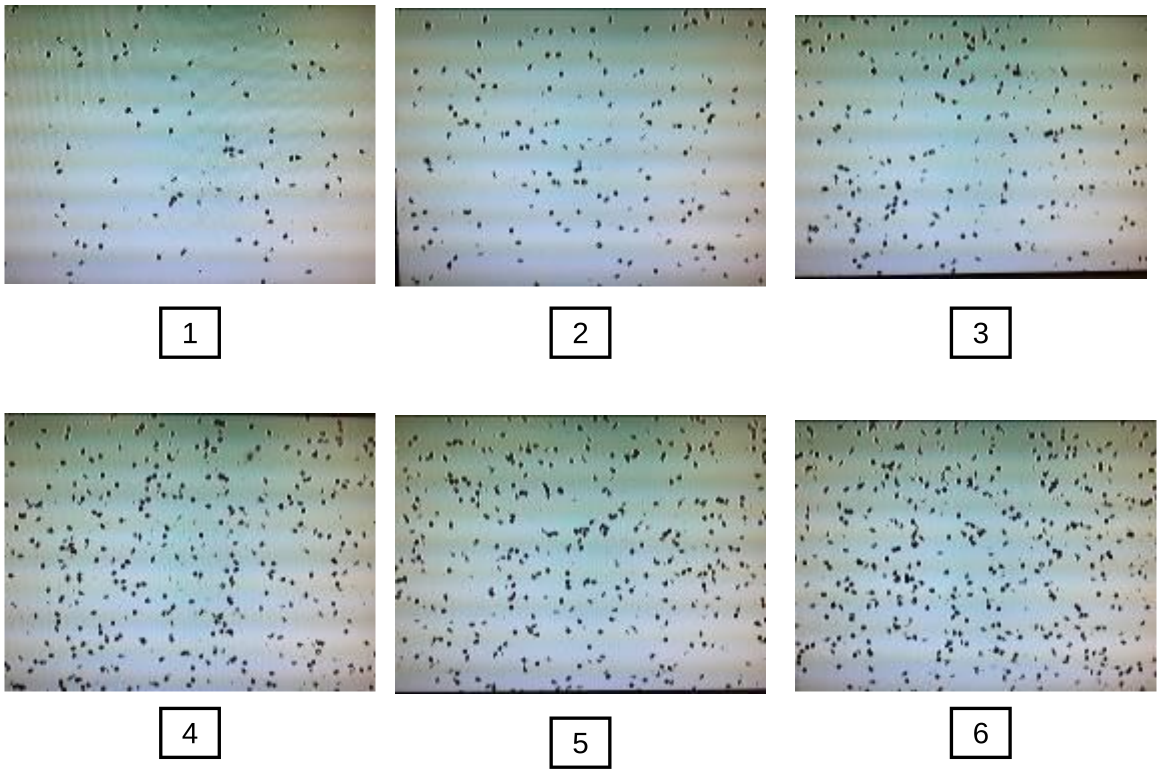

Figure (6): Magnified tracks in CR-39 with the number of filters indicated to which each detector was exposed. Note overlapping tracks at higher track density.

From Tables 2 and 4, it is obvious that the net track densities observed on the bare detectors were different between the two exposure periods. Likewise, from Tables 3 and 5 the same is obvious for the enclosed detectors. This is because the total exposures to radon in terms of Bq-hours/m^3 (pCi-days/liter) were different between the two exposure periods. What is of interest here is the relative responses between the bare and enclosed detectors for each exposure period. Table 6 shows, for each surface and each exposure period, the ratio of the average net track density of the bare detectors to that of the enclosed detectors. These values are shown graphically in Figure (7). In that figure, the error bar on each column is ± two times the standard deviation around the value of the ratio.

Table 6. Ratio of net track density, bare detectors to net track density, enclosed detectors

Particle Conc.	A	B	C	D	E
Low	3.20 ± 0.11	3.58 ± 0.11	3.27 ± 0.29	3.14 ±0.06	3.60 ±0.18
High	1.96 ± 0.10	2.04 ± 0.22	1.99 ± 0.10	1.89 ± 0.03	2.07 ± 0.10

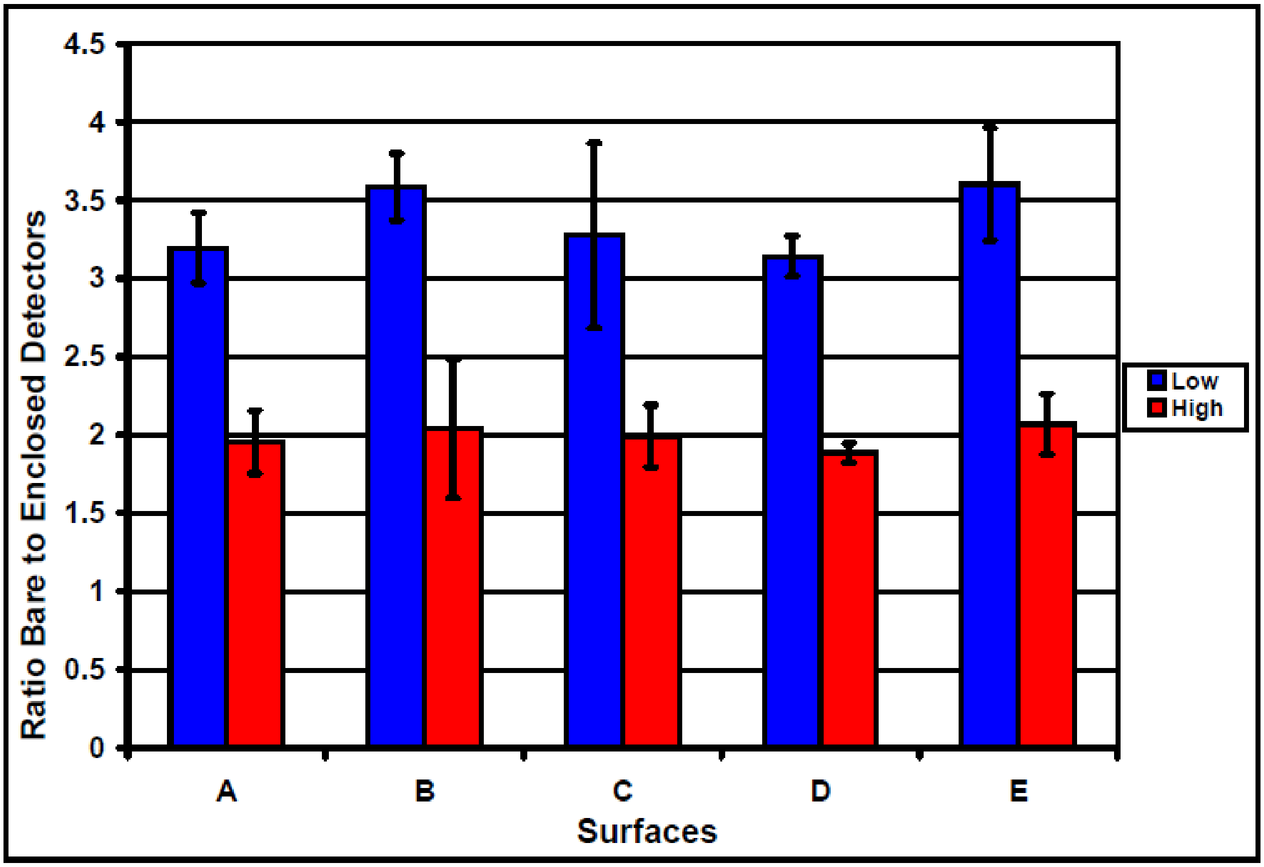

Figure (7): Ratios of average net track densities of bare to enclosed detectors with low and high particle concentrations

It is seen from Figure (7) that there is some variation among the surfaces in the ratio of bare to enclosed detector responses. Just from inspection of the error bars, it appears, for the exposure with low particle concentration, that the ratios for Surface B and D may be significantly different. No statistical analyses were done to determine this. Even if true, it is difficult to interpret what that might mean. But it is interesting to note from Figures (4) through (5) that the variation across Surface D was consistently smaller than the variation across the other surfaces. Surface D was the farthest from the chamber door, but it was also the farthest away from shelves in the chamber. It is not clear if this was a factor, or perhaps if the pattern of air flow in the chamber was a factor.

What is most important to note is the obvious difference in the ratios of bare to enclosed detectors between the two exposure periods with different conditions of particle concentration and radon progeny equilibrium. Ignoring any differences among surfaces, the overall ratio of the responses of the bare to enclosed detectors for the exposure with a low particle concentration was 3.35 ± 0.20; whereas, the same ratio for the exposure with a high particle concentration was 1.99 ± 0.15. Because the enclosed detectors respond only to radon diffusing through filters, they should not be affected by radon progeny outside of the enclosures. Therefore, this difference is due to the effect of particle concentration, and radon progeny equilibrium, on the bare detectors. The average difference observed in the study was $(3.35 \pm 0.20)/(1.99 \pm 0.15)$ or a factor of $1.69 \pm$

0.16. In other words, the response of bare detectors was 69% larger when the particle concentration and radon progeny equilibrium were low than when they were high. This difference in response was due to the increased deposition of radon progeny onto the surfaces of the bare detectors.

Conclusions

The results of this study provide evidence that alpha particles emitted from radon progeny on the surface of CR-39 produce observable tracks. Also, the response of bare CR-39 detectors is significantly affected by the concentration of particles in the air due to the tracks from radon progeny deposited on their surfaces. This is due to more deposition of radon progeny when the concentration of particles in the air is low than when it is high. There is some evidence that the orientation of detectors in relation to nearby shelves and perhaps the pattern of air flow in the Bowser-Morner chamber, both of which could affect the amount of deposition of radon progeny, may also have affected the responses of the bare CR-39 detectors.

Acknowledgement

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MINNESOTA DEPARTMENT OF HEALTH'S RADON RESISTANT NEW CONSTRUCTION EFFECTIVENESS STUDY

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Abstract

This study assessed the effectiveness of Radon Resistant New Construction (RRNC) practices as installed by licensed residential contractors in Minnesota homes. Since June 2009 all new Minnesota homes have been required by either the state energy or building code to have passive RRNC features installed to reduce indoor radon levels. These passive features have been found to have varying levels of effectiveness, largely dependent on the installation practices. The primary goals of this study were to evaluate: 1. The radon concentrations in an estimated 800 Minnesota homes with 'as-built' passive RRNC features; 2. The change in radon concentrations when 100 of these passive RRNC homes are converted to active RRNC; and 3. The radon concentrations in 100 'as-built' active RRNC homes with features consistent with the MDH Gold Standard. Results from this study showed a decrease in the number of new homes built with elevated radon concentrations and a very successful radon reduction rate for those homes that were activated.

Introduction

According to the World Health Organization, exposure to radon gas has been attributed to an increase in lung cancer in humans (Zeeb & Shannoun, 2009). As a public health entity, the Minnesota Department of Health (MDH) has an established outreach and education program regarding radon in Minnesota homes. A primary prevention strategy for reducing the public's exposure to radon gas is to build new homes with radon resistant construction features, also known as radon resistant new construction (RRNC). These construction features include an air-permeable layer of gravel below the poured concrete floor, a soil-gas retarder, a radon vent stack running from the sub-slab zone up through the roof, and slab sealing.

RRNC features have been shown to reduce indoor radon concentrations in homes by a varying degree. In its 'Building Radon Out' publication, the US Environmental Protection Agency (USEPA) reports passive RRNC reduces radon by an average of about 50%, while an active system provides even further reduction (USEPA, 2001). In its 'Consumer's Guide to Radon Reduction', the USEPA reports passive sub-slab suction typically reduces radon by 30-70%, but adds it is not as effective as sub-slab suction, which typically reduces radon by 50-99% (USEPA, 2013).

To evaluate whether these reduction figures are accurate for Minnesota, MDH reviewed studies that measured radon reductions in passive RRNC. Overall, the studies indicated USEPA's reduction figures are slightly high for passive RRNC. A more accurate reduction range appears to be about 20 – 60%. Reviewed studies all show radon reduction in this range (Arvela, 2011; Burkhart, 1991; Dewey, 1994; Groves-Kirkby, 2006; LaFollette, 2001; Scivyer, 2001). There is less research on active RRNC with reductions in active systems ranging from 70-93% (Burkhart; Dewey; Groves-Kirkby). Some of these studies may not have been considered in the USEPA analysis, especially Arvela et al., the largest RRNC study conducted to date. The Arvela et al. study is most comparable to Minnesota, due to RRNC building requirements and climate similarities, and showed a radon reduction of between 21-57%.

From this literature review, MDH concluded that passive RRNC can achieve, on average, a 40% reduction while active RRNC can achieve at least an 80% reduction. Considering the average radon concentration in Minnesota homes is 4.2 pCi/L, this suggests passive RRNC homes should achieve a reduction to about 2.5 pCi/L, while active RRNC homes should achieve a reduction to about 0.8 pCi/L.

The 0.8 pCi/L outcome in homes with active RRNC is given further credibility by two data sets. First, Steck (2008, 2012) found an average radon level of 0.8 pCi/L in 123 homes that had been mitigated with active soil depressurization (ASD). Second, unpublished MDH data collected from 84 Minnesota radon mitigation contractors between 2007 to 2014 has shown an average concentration of 1.1 pCi/L (median=0.8 pCi/L) was achieved after mitigating 10,896 existing homes that did not have RRNC features.

Angell's (2012) meta-analysis of RRNC studies concluded that, when installed to recognized standards, RRNC may reduce indoor radon levels by about fifty percent. Additionally, he called for further research to address the effectiveness of RRNC in a random survey of homes. This MDH research project begins to address this research need by assessing the effectiveness of RRNC practices, as installed by licensed residential contractors in Minnesota. Since June 2009 all new Minnesota homes have been required by the state energy or building code to have passive RRNC features installed to reduce the radon levels (MN Revisor, 2014). These passive features have been found to have varying levels of effectiveness, largely dependent on the installation practices.

An active RRNC home has better air flow due to clean aggregate under the entire slab, compared to a properly installed ASD system, which is connected to a suction pit or drain tile system. Hence, it is reasonable to infer an active RRNC should yield a lower reduction than an ASD home to below 0.8 pCi/L, and possibly as low as 0.3 pCi/L. To study this hypothesis, MDH measured radon levels in new homes constructed with RRNC features in Minnesota. Both passive and active RRNC homes were tested and radon levels were compared.

The primary goals of this study were to evaluate: the radon concentrations in an estimated 1,000 Minnesota homes with 'as-built' passive RRNC features as compared to MDH data in existing homes not built with RRNC features; the change in radon concentrations when 100 of these passive RRNC homes were converted to active RRNC; and the radon concentrations in 100 'as-built' active RRNC homes with features consistent with the MDH Gold Standard.

Methodology

The MDH study evaluated two methods for the protection against exposure to radon in new construction. The first, and most common method, involves building homes with passive RRNC features, then testing the home for radon and finally activating any passive systems if the radon is elevated. The second method involves installing a fan to activate the RRNC system in all new homes from the beginning of construction and eliminating the need for any pre-activation radon testing.

Participant Recruitment

Radon concentrations were assessed in 13 of the 14 Minnesota counties that had the largest number of new homes built from January 2010 to September 2012. Due to the difficulties of obtaining the property records from every MN county, including time constraints and costs, as well as the variability of building code enforcement in greater Minnesota, MDH decided to focus on 13 of the largest counties with the most building permits reported. This information was gathered from the US Census Bureau's Construction Permits website (US Census Bureau, 2015). Only the homes with a permit issued after June 1, 2009 are required by Minnesota law to have a passive RRNC system. Because some builders take longer than seven months to build a home or have model homes built prior to June 1, 2009, the beginning date of January 1, 2010 was selected.

Each county property tax records department shown in Table (1) was contacted and electronic property tax records were obtained for all new homes built from January 1, 2010 to September 30, 2012. Because of the difficulty in obtaining tax records for St. Louis County, they were eliminated from the study.

County Name	**Number of Letters Sent**	**USEPA Zone Designation**
Anoka	1,438	Zone 2
Carver	1,002	Zone 1
Chisago	39	Zone 2
Dakota	832	Zone 1
Hennepin	1,851	Zone 1
Isanti	47	Zone 2
Olmsted	548	Zone 1
Ramsey	224	Zone 1
Scott	846	Zone 1
Sherburne	148	Zone 1
Stearns	305	Zone 1
Washington	1,111	Zone 1
Wright	171	Zone 1
Totals	**8,562**	

Table (1): Participating counties, the number of homeowner recruitment letters sent by MDH to new home owners and the USEPA's Zone designation.

The homeowner recruitment letters and surveys were sent to 8,562 new home owners in November 2012. Most of the letters were sent around the Twin Cities metropolitan area as this was where the majority of the newly built homes are located. However, some homeowners outside the metro area also received letters. Figure (1) shows the locations of the homes receiving the MDH letters. An example letter and survey is shown in the Appendix. These letters introduced the homeowner to the difference between passive and active RRNC features, offered the opportunity to receive a free radon test kit, and described the potential for some homes to receive a free radon mitigation fan.

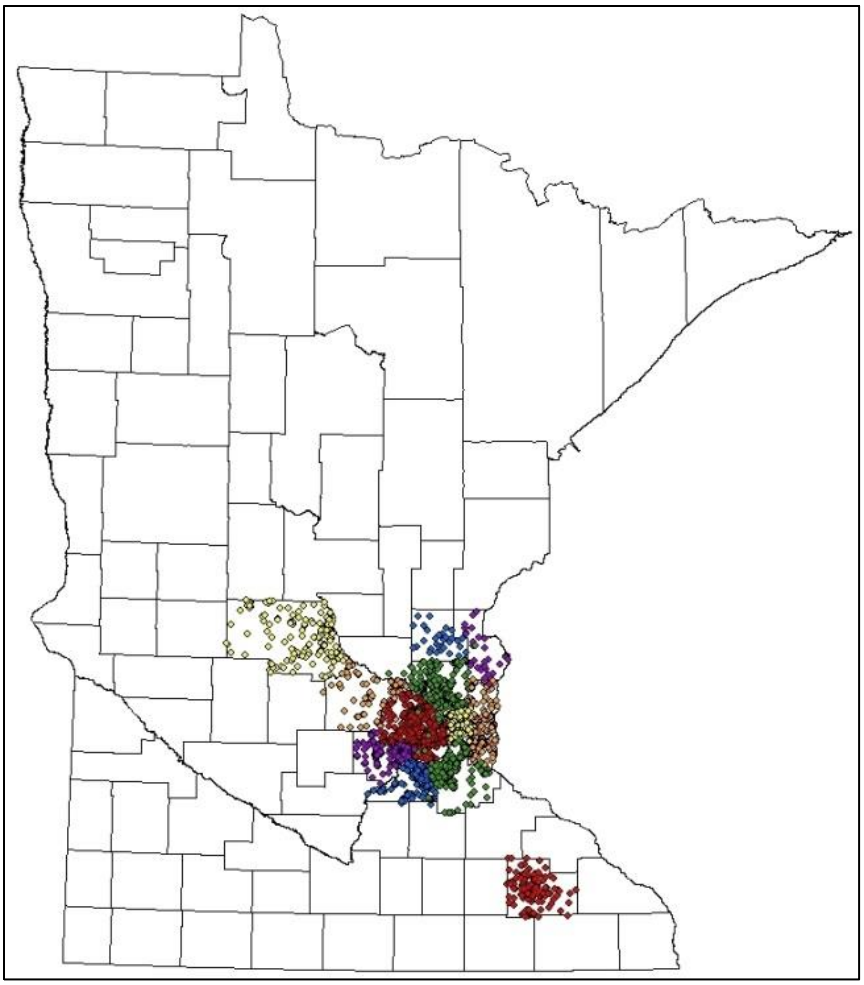

Figure (1): Locations of homes receiving the homeowner recruitment letters.

Participating property owners were invited to complete the enclosed survey, sign the informed consent form, and return it to MDH to receive their free radon test kit. Testing was to be completed as soon as possible, preferably before the end of the heating season (November through March). The majority of the pre-activation test kits (94%) used were placed during the heating season.

Approximately 500 of the recruitment letters were returned to MDH marked as "return to sender," which meant about 8,000 letters received by new home owners. MDH received 1,144 completed surveys (response rate of 14.3%) with 1,125 homeowners requesting a radon test kit to participate in the study.

Passive RRNC Activation and Testing

Radon fans, at no cost to the owner, were offered to 100 homes with elevated radon levels that met the basic eligibility criteria. In order to be eligible for a free fan, participants needed to return a completed survey, have a passive system in their home, indicate they will hire a contractor to install the fan, or install it themselves, and sign the informed consent section of the survey. These fans were allocated to each county based on the ratio of permits reported in the county versus the total number of permits in the study area. For example, Hennepin County reported having 1,851 new homes built out of a total of 8,562 homes in the study area. Because Hennepin County had 21.6% of the permits reported, 22 fans were originally allocated for the county.

The first homes to report elevated radon results were offered fans until the county allotment had been distributed. A radon fan, U-tube pressure gauge, and a follow-up test kit were sent as a package to these first homeowners. The homeowners agreed to either hire a professional to install the mitigation fan or to install it themselves, and then conduct a follow-up radon test with the kit provided. The radon mitigation fans used were selected based on Minnesota Building Code requirements for moving 50 cubic feet of air per minute (CFM) at 1/2 inch of water column. In most cases, fan model RP140 from RadonAway[1] was used. If post-activation radon testing continued to show elevated radon levels, a consultation with the homeowner was conducted. Consultations may have led to a site visit, a fan swap-out, or both. If the fan needed to be swapped for a larger model, an RP145 from RadonAway was used.

Testing Homes Built with Active RRNC

Another approach to reducing radon in homes is to install an active RRNC system from the very beginning of home construction. This approach includes all of the RRNC features as discussed earlier, but also includes a radon mitigation fan installed in the attic on the passive vent riser. Some home builders have decided to bypass the initial radon testing process and simply install a small, low-powered radon fan without conducting any initial radon testing. The radon fans used for this approach were the same fans used to activate passive RRNC. The recruitment of these houses was handled the same way as the passive only houses discussed above, and the homes were identified by homeowner answers on their completed survey.

Test Kit Quality Assurance and Quality Control (QA/QC)

The radon test kits used were provided by Air Chek.[2] Each shipment of 100 test kits sent from Air Chek to MDH was put through the MDH Quality Assurance and Quality Control (QA/QC)

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(1) RadonAway®, Ward Hill, MA. http://www.radonaway.com/
(2) Air Chek, Inc., Fletcher, NC. NRPP Device Code 8200. http://www.radon.com/

system. Five test kits from each box of 100 kits were sent to the Bowser-Morner[3] reference chamber to be spiked. Spikes were sent to the chamber in batches of 100 and conducted monthly through the heating season. Each batch of spikes showed very good accuracy with none of the spiked samples falling out of the control limits agreed upon by MDH and Air Chek.

In addition, one test kit from each box of 100 was held by MDH and submitted to Air Chek as a blank to identify any potential compromised test kits due to increased moisture in the charcoal or radon leaking through the packaging. All of the blanks submitted showed radon lower than Air Chek's lowest limit of detection and moisture levels below 4%, the threshold agreed upon between MDH and Air Chek to determine if the kits were taking on too much moisture. Finally, MDH monitored the radon and humidity levels in the test kit storage location to ensure quality was not compromised.

Discussion of Results

Based on the completed surveys, participants reported newly constructed homes built by 261 different builders in 132 different cities. The number of participants in a given city ranged from 1 to 97, and the number of homes built by a specific builder ranged from 1 to 90. Approximately 18% of respondents did not fill out the builder's information on the survey. In addition, the survey did not ask what type of home the respondents lived in, so it is unknown whether the responses came from single family homes or two-, three-, or four-unit townhomes. The foundation type was also not reported.

Table (2) shows the responses to the questions asked on the MDH Radon Study Survey & Informed Consent form. A total of 1,144 surveys were returned with the vast majority of respondents requesting a radon test kit.

Question	Yes	No	Don't Know	Left Blank	Total
I am the current homeowner	1,132	2	--	10	1,144
There is a passive vent pipe installed	737	35	362	10	1,144
There is a fan installed on the radon system	50	599	485	10	1,144
Requested MDH test kit to test the home	1,125	5	4	10	1,144
Requested to be eligible for a free radon fan	1,014	45	74	11	1,144

Table (2): Summary of answers to "MDH Radon Study Survey & Informed Consent" form.

MDH distributed 1,125 radon kits to study participants and 894 homeowners tested their homes (79.5% usage rate) with 842 valid test results returned (74.8% valid test rate): 805 passive homes and 37 active homes. The remaining 231 homeowners either did not use their test kit, or it was not received by the lab for analysis. Five of the returned radon results were removed from the study because the homes were either built prior to the inception of the RRNC code or were outside the study area. A total of 47 test kits returned an invalid result due to missing information, testing for too long of a time period, or delay in shipping the kit back to the lab.

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(3) *Bowser-Morner Radon Reference Chamber, Dayton, OH. http://www.bowser-morner.com/*

Table (3) summarizes the radon results of passive systems tested in each of the participating counties along with the number of homes with elevated radon and the median radon results for each county. The right side of Table (3) is a summary of all radon tests reported in existing housing to MDH by radon labs through 2010. According to MDH, an estimated 40% of existing homes in Minnesota will have a radon level at or above 4.0 pCi/L (MDH Website, 2015). The dataset shows 37% of existing radon tests conducted in the 13 participating counties had elevated radon levels, with a median result of 3.1 pCi/L. However, among the 805 passive systems tested, only 164 homes (or 20%) had elevated radon levels, with a median result of 1.9 pCi/L. The maximum result found in all passive homes was 38.2 pCi/L.

Passive Homes Tested (2012-2013)					**Existing Tests in MDH Database (1988-2010)**			
County	**Homes tested**	**≥4 pCi/L**	**% ≥ 4pCi/L**	**Median (pCi/L)**	**Total Tests**	**≥4 pCi/L**	**% ≥ 4pCi/L**	**Median (pCi/L)**
Anoka	87	4	5%	1.10	5,827	1,199	21%	1.90
Carver	108	20	19%	2.05	7,031	2,605	37%	3.10
Chisago	7	0	0%	1.90	1,467	402	27%	2.30
Dakota	84	21	25%	1.95	13,190	4,896	37%	3.10
Hennepin	192	34	18%	2.00	49,875	19,000	38%	3.20
Isanti	2	0	0%	1.35	630	101	16%	1.80
Olmsted	62	31	50%	3.80	7,291	3,707	51%	4.00
Ramsey	32	9	28%	1.80	17,641	5,189	29%	2.60
Scott	70	18	26%	2.25	2,150	1,037	48%	3.80
Sherburne	6	3	50%	4.05	4,487	1,985	44%	3.50
Stearns	30	9	30%	2.65	7,970	3,590	45%	3.50
Washington	112	12	11%	1.30	9,699	3,297	34%	2.78
Wright	13	3	23%	2.30	6,469	2,944	46%	3.60
TOTALS	**805**	**164**	**20%**	**1.90**	**133,727**	**49,952**	**37%**	**3.10**

Table (3): Radon test results from passive homes tested and county test results in the existing MDH database.

It is difficult to compare passive results with the existing tests in the MDH database due to the very small sample size in some counties (Chisago, Isanti, Sherburne and Wright). However, the counties with more passive system results do show a decrease in the median radon results. Each of the counties with at least 30 passive systems tested showed lower median radon concentrations as compared to the existing county medians in the MDH database, one by more than 50%.

Homes with passive systems in the Twin Cities metropolitan area counties (Anoka, Carver, Dakota, Hennepin, Ramsey, Scott and Washington) had consistently lower median radon levels, by 39%, compared to tests results of the general housing stock (1988-2010). In contrast, Olmsted and Stearns counties, which are located outside the metro area, showed smaller average differences in median radon levels of 5% and 24%, respectively. It is not clear why the radon difference percentages in these counties were lower than the metro area counties.

Once the passive systems were activated, a sharp reduction in the radon levels was observed. A total of 71 homes returned a valid test result after system activation. Table (4) shows the county activation results along with the median and average reduction. Overall, the median radon reduction for homes with an active system was 94.2%, the average radon reduction was 89.0%, and the highest radon reduction was 98.9%. The median post-activation concentration was 0.3 pCi/L. The maximum result found in all homes with active systems was 4.8 pCi/L.

In 67 of 71 homes where a system was activated, the radon levels were reduced to below 4.0 pCi/L with the smaller radon fan (RP140, RadonAway). However, there were four cases where system activation alone was not successful in reducing radon levels below 4.0 pCi/L. Two of these homes were shipped a larger fan, but no further radon testing has been reported and MDH follow-up with the homeowner has been unsuccessful to date. In the other two homes, radon levels were reduced after consulting with the homeowner and replacing the existing fan with a slightly larger model (RP145, RadonAway). One of these homes also lacked all of the construction details required by the building code: specifically, there was no slab sealing or gravel layer under the slab. The other home had a very large basement footprint of approximately 8,000 square feet. When the small fan was switched for the larger fan, the radon levels were reduced below 4.0 pCi/L.

Passive Homes Activated					
County	**Homes Activated**	**Median Passive Result (pCi/L)**	**Median Active Result (pCi/L)**	**Median Reduction**	**Average Reduction**
Anoka	3	4.7	0.3	92.9%	92.2%
Carver	8	5	0.3	93.4%	86.0%
Chisago	0	--	--	--	--
Dakota	10	6.75	0.4	93.9%	87.9%
Hennepin	18	6.45	0.3	94.7%	86.7%
Isanti	0	--	--	--	--
Olmsted	8	14.15	0.65	94.0%	87.9%
Ramsey	3	5.9	0.3	94.9%	95.9%
Scott	9	6.8	0.3	95.0%	91.7%
Sherburne	2	11.8	0.3	97.4%	97.4%
Stearns	3	5.4	0.7	80.6%	83.4%
Washington	6	8.9	0.3	94.6%	93.6%
Wright	1	4.2	0.3	92.9%	92.9%
TOTALS	71	6.60	0.3	94.2%	89.0%

Table (4): Number of activated systems per county and the median and average radon reduction after system activation.

A total of 126 homes were offered a free radon mitigation fan. Only 105 of these homes were shipped a fan package. To date, 71 of these homes have reported installing the radon fan and having a valid post-activation radon test result. Follow-up with the remaining home owners has been unsuccessful, so it is not known if the radon fans were received or installed. Radon test kits shipped with these fans were never returned for the lab for analysis. Although specific data was not collected, some homeowners did report to MDH that they opted to purchase and install their own radon fan.

MDH has created a voluntary designation that includes the installation of active RRNC features, branded the Gold Standard for Radon Resistant New Construction (MDH, 2015). In order to become a Gold Standard builder, a building contractor needs to commit to offering an active radon system as part of the completed home. To date, MDH has recruited 115 builders that either offer the active system as an additional option or include it in the final building construction.

The second part of the project looked at the radon-reduction performance of homes built with active RRNC as part of the MDH Gold Standard RRNC Program. Table (5) shows the summary of these 'as-built' active RRNC homes, 37 homes tested as part of this study. Because the dataset is small compared to the passive homes shown before, it is difficult to make any comparisons from county to county. However, it is important to note active RRNC homes showed low radon levels in nearly every home tested.

'As-built' Active RRNC Homes			
County	**Homes Built**	**Median Result (pCi/L)**	**Average Result (pCi/L)**
Anoka	0	--	--
Carver	6	1.7	2.0
Chisago	0	--	--
Dakota	3	0.3	0.7
Hennepin	13	0.7	0.8
Isanti	0	--	--
Olmsted	5	0.3	0.6
Ramsey	2	0.6	0.6
Scott	4	0.8	0.9
Sherburne	0	--	--
Stearns	0	--	--
Washington	4	1.1	1.4
Wright	0	--	--
TOTALS	37	0.6	1.0

Table (5): Number of 'as-built' active RRNC homes tested and the median and average radon levels.

Of the 37 'as-built' active RRNC homes tested, the median radon test result was 0.6 pCi/L and the maximum radon level measured was 4.3 pCi/L. Only one 'as-built' active RRNC homes had radon levels above 4 pCi/L. Because MDH did not provide any on-site system inspections, it is not known why the home had elevated levels of radon. Follow-up with the homeowner has also been unsuccessful to date.

Conclusion

The MDH RRNC study evaluated the likelihood of: homeowners to test for radon when educated about the passive radon system installed in their home; their likelihood of activating the system if necessary, and completing the post-activation radon test. In addition, we assessed the effectiveness of builder-installed passive RRNC systems in different parts of the state, by different builders and where code competency and enforcement may vary. Finally, we evaluated the effectiveness of converting passive RRNC systems to active systems.

Approximately 8,000 homeowner recruitment letters were received by owners of new Minnesota homes. The response rate to these letters was 14.3% and the test kit usage and valid test result rates from the participants was over 70%. More than 800 radon tests results from 'as-built' passive RRNC homes in 13 Minnesota counties showed a reduction in the median radon levels of 39% as compared to the existing tests in the MDH database. Individual county median radon reductions where a minimum of 30 systems were tested varied between 5%-53%. These reductions are consistent with previously cited literature.

Limitations of this study

Due to many confounding factors, only the most populated areas of state were included in this study. Results may not be representative of the entire state for several reasons. For instance, there are sparsely populated areas of the state that may have little or no building code enforcement or only select codes are enforced. In addition, other changes have been made to the Minnesota building and energy codes over the past 15 years, including air sealing and additional ventilation requirements. This study did not look specifically at these code changes.

Additionally, some of the participating homeowners may not have a thorough understanding of the construction practices and materials used in their home. Many new homes are built by contractors in the hope of selling the home, and therefore the buyer of the home was not involved in the construction process. In addition, we cannot guarantee the answers given on the survey were completely accurate as MDH did not visit most of these 'as-built' houses to inspect the RRNC features that may have been included. MDH also did not visit any of the houses during the construction process to inspect the RRNC features nor was house or foundation type reported. Due to not inspecting the RRNC systems, it is not known why some passive systems may have failed.

All of the radon testing was short-term (3-7 days) and conducted by the occupant of the home. We assume the tests were conducted correctly if a valid test result was reported by the laboratory. The assumption is homeowners read and followed the instructions provided by the test device manufacturer. However, because a trained person did not place the test devices, it is impossible to know if the test location selected was valid or if closed-house conditions were maintained. The latter is part of the reason for testing during the heating season in Minnesota.

A further limitation of this study is the lack of successful follow-up with participants. Many attempts were made to contact participants who had invalid test results due to incomplete test kit data both for the initial passive testing round and also the passive to activation round. Some of the homeowners notified the laboratory of the correct information and a valid test result was reported. However, follow-up with homeowners who were offered a radon mitigation fan versus those who accepted the offer was lower than MDH anticipated. Most follow-up letters and emails from MDH went unanswered, and therefore no further action occurred. Some of these homeowners may have moved, became disinterested or disheartened by either not being offered a radon fan originally or not successfully filling out test kit information. It is not known what percentage of non-respondents installed their own radon fans and chose to not participate further, or which homeowners did not receive follow-up notices from MDH due to email or postal issues.

Finally, the passive systems tested were never capped or otherwise made non-operational. This makes knowing the radon value in homes without the RRNC features in the same housing stock as those tested in this study impossible to measure. Due to the risk of increasing indoor radon levels and exposing participants to additional carcinogen concentrations during a time of non-system operation, this type of study design was not attempted. A study comparing capped versus un-capped RRNC systems in occupied homes is too resource-intensive and would not gain approval of our agency's Internal Review Board.

Need for future research

Additional research looking specifically at existing housing stock built under different building and energy codes would help identify which construction technique(s) have the largest impact on indoor radon levels. Because building codes change every few years, identifying and testing 'as-built' homes with these different codes may aid in future code development.

Identifying areas of the state where the radon levels have not been reduced with passive RRNC is also important. If specific areas are not showing a reduction in radon concentrations, a more detailed investigation into builder and code official education can be implemented. In addition, expanding this study and its lessons learned to incorporate the more than 30,000 homes built in Minnesota since this study ended will help improve the size of the dataset and the conclusions drawn.

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Appendix

MINNESOTA MDH DEPARTMENT OF HEALTH

Protecting, maintaining and improving the health of all Minnesotans

Date

Dear Resident,

In June 2009, the Minnesota state building code was changed to require radon reducing features in all new homes. Radon is a soil gas that causes an estimated 21,000 lung cancer deaths each year in the United States. The Minnesota Department of Health (MDH) is conducting a research study to determine how much the current building code may reduce radon levels.

MDH would like to offer you a free radon test kit that you can conduct yourself. In addition, for the first 100 homes with elevated radon, MDH will provide a free radon mitigation fan, which can be connected to your current system to further reduce the radon levels in your home.

More information regarding radon in Minnesota can be found at the MDH radon webpage: www.health.state.mn.us/radon

If you would like to participate in this study, complete the enclosed survey, sign the consent section and return to MDH at the address listed on the survey. If you have questions about this project contact Joshua Miller by phone or email listed below.

Sincerely,

Joshua Miller

Joshua Miller, Building Scientist
Joshua.Miller@state.mn.us
651-201-4621
Indoor Air Unit
Minnesota Department of Health
P.O. Box 64975
St. Paul, MN 55164-0975

General Information: 651-201-5000 • Toll-free: 888-345-0823 • TTY: 651-201-5797 • www.health.state.mn.us
An equal opportunity employer

2012 Radon Study Survey & Informed Consent

Address: ______________________________________ **Return this completed form to:**
Minnesota Department of Health
Indoor Air Unit
PO Box 64975
St. Paul, MN 55164-0975

City: ______________ MN Zip: ______________

Yes	No		I am the current property owner
Yes	No	Don't Know	There is a passive radon vent pipe running from under the basement floor and out the roof.
Yes	No	Don't Know	There is a fan installed on the radon system
______________________			Is the builder of my home
Yes	No	Don't Know	I would like MDH to send me a free radon test kit so that I can test my own home. ($15 value)
_____________(initial)			If I request a test kit from MDH, I will use the test kit to test the address listed above.
Yes	No	Don't Know	I would like to be eligible to receive a free radon fan ($150 value), if my home has an indoor radon level above 4.0 pCi/L.
_____________(initial)			If I request a radon fan I understand that I will have to hire a contractor to install the fan at a cost to me of approximately $200 - $400.
_____________(initial)			If I request a radon fan I agree to complete a second radon test, provided by MDH, after the fan has been installed and in the same location as the first test.

Data Privacy:
The data collected by the MDH is for research purposes and will allow for a better understanding of the indoor radon risk that may be found in newer Minnesota homes. This information is considered private and cannot be shared by MDH with other parties. You will not be identified in any public reports created by MDH. Your participation in this data submission is completely voluntary.

Risks and Benefits:
Through this study, you may identify that your home has elevated indoor radon levels, which is known to cause lung cancer. Elevated radon levels can be reduced in virtually every home with a properly installed radon reduction system that includes a fan. Through this study, you will receive free radon testing and the first 100 homes with elevated radon will receive a free radon mitigation fan. Depending on how the fan is installed and any defects in the construction of your home, it is possible that indoor radon levels will not be reduced. In rare cases, back-drafting from combustion appliances might occur; a safety check of your appliances should be conducted after installation of the fan.

If you have questions about this study or how the data will be stored and used by MDH, please contact Joshua Miller at 651-201-4621 or joshua.miller@state.mn.us

Print Name: ____________________________ Sign: ____________________________

Date: ______________

MEASUREMENT OF RADON IN NATURAL GAS AND IN PROPANE USING ELECTRET ION CHAMBERS

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Abstract

Electret ion chambers (known by the trade name E-PERM® [2]) have been extensively used for measuring indoor and outdoor radon concentration in air. In view of the recent interest in measuring radon in natural gas, research is initiated to devise arrangement for sampling and analyzing radon in natural gas. Natural gas is chemically very different from air both in terms of density and ionization potentials (energy needed to produce one ion pair) and is expected to have a response different from that of air. Further, electret ion chambers (EICs) use ionization measurements compared to alpha counting used in scintillation cells, the other technique standardized for measuring radon in natural gas. Research results are presented in this paper, intercomparing the two technologies for measurement of radon in natural gas. When radon is measured in natural gas using scintillation cells, the calibration factors derived for air are used. The results need to be divided by a correction factor *f* to arrive at proper results. Kitto determined this factor experimentally to be 1.07 for scintillation cells. The current work determined this factor for EIC to be 1.10, only slightly different from the correction factor for scintillation cells. Large numbers of intercomparison experiments are conducted by collecting the samples from the same source at the same time, both by the EIC system and by scintillation cells. Results indicated excellent agreement confirming the performance of the sampling and analysis system for EIC. The *f* factor was found to be 1.36 for propane when measured with EIC.

Key words: scintillation cell, electrets, electret ion chamber, natural gas, propane, W values

(1) The authors are the developers of, and have a commercial interest in, the Electret Ion Chambers discussed in this paper.
(2) Rad Elec, Inc., 5716-A Industry Lane, Frederick, Maryland 21704

Introduction

Natural gas is widely used as a domestic fuel for cooking, heating and many other applications. The sources of natural gas can be from natural gas producing wells or from the natural gas produced by hydraulic fracturing of shale located deep in the ground. In all cases the natural gas comes from the ground and is expected to have radon accompanying it. The natural gas in the pipelines closer to the wells may have more radon than the pipelines farther away from the source because of the radioactive decay of radon. There is a possibility of leakage of natural gas containing radon into the ambient air. Radon can be released into a home through the combustion or burning of natural gas.

The measurement of radon in natural gas has been of interest for a long time. Due to their sensitivity and ease of use, alpha scintillation cells are being increasingly used for the measurement of radon in natural gas. Most of the available data on radon in natural gas in existing literature is based on the use of these devices. Usually the calibration constants standardized for measuring radon in air are used to calculate radon concentration in natural gas. Recently, Kitto (2014) and Jenkins (2014) indicated that the calibration constants derived for measuring radon in air are not appropriate for calculating radon in natural gas due to inherent differences in density. After a series of experiments, Kitto (2014) concluded that the correction factor is 1.07 when measured at atmospheric pressure and at room temperature. That means the measured radon concentration in natural gas using calibration constants for air need to be divided by 1.07 to calculate the correct results. This is termed in this presentation as the *f* factor. It is also pointed out by Jenkins (2014) that such factors can be different at various elevations, due to different pressures at the corresponding elevations.

Electret ion chambers (EICs), which are widely used for indoor and outdoor radon measurements, can also be used for measuring radon in natural gas. These have been used by Nenznal (1996) for a large number of radon measurements in natural gas within the concentration range of 132 to 195 pCi/L. He has also made a few measurements using scintillation cells in order to confirm the results from the EICs. The EICs work on a very different principle (ionization) compared to scintillation cells (alpha scintillation counting). The object of the present work is to determine the correction factor *f* for measurements of radon in natural gas using EICs.

The final purpose of the current work is to intercompare the results as measured by scintillation cells and as measured by EICs from a sample taken from an identical source. For this purpose, the same natural gas is sampled both by scintillation cells and by EICs. Scintillation cells are sent to Dr. Kitto for analysis. EICs are analyzed at Rad Elec labs. Results are compared and discussed in light of the technological differences. There is an important difference in analyzing the sample between scintillation cells and EICs. The samples collected by scintillation cells can be analyzed after a delay of 4 hours or more; whereas, the sample collected by an EIC has to be held for some period in the sampling device (1 to 8 days) before proper analysis is possible. A delay correction needs to be applied in order to calculate radon concentration at the time of collection. Delay corrections are also needed if the scintillation cell is analyzed after a known delay.

Commercially available propane is another gas used as fuel for cooking. This is not expected to have radon simply because it is obtained by distillation of crude oil, not from the ground as in the case of natural gas. The only distinction is that the density of propane (1.5 relative to air) is very different from that of natural gas (which is predominantly methane) with much lower density. It is of interest to determine the correction factor *f* for radon in propane gas only as the demonstration of the technique.

The significance of measuring radon in natural gas

Wojcik (1989) has done the calculation of the release of radon into a home atmosphere via burning of natural gas. The following parameters were assumed in Wojcik's experiment: the radon concentration in natural gas is 235 Bq/m^3 (6.4 pCi/L), the kitchen volume is 25 m^3, there are three air changes per hour, daily gas consumption is 1 m^3, and a cooking time of two hours per day. In this scenario, the mean radon concentration of 40 Bq/m^3 (1.1 pCi/L) will be raised by 1.5 Bq/m^3 (0.05 pCi/L) during cooking time and by only 0.13 Bq/m^3 (0.004 pCi/L) on a daily average. These calculations indicate that there is no appreciable contribution to radon in indoor air by the use of natural gas in homes. The situation can be different if the air exchange rate is different than what is assumed or radon concentration in natural gas is different than what is assumed.

Early studies by USGS reported well head concentrations between 0.2 to 1450 pCi/L (Johnson, 1973), Devonian shale level of 151 pCi/L (Gogolak 1980), and Marcellus shale levels of 1 to 79 pCi/L with an average of 37 pCi/L (Rowan 2012). The current studies indicated a measured radon concentration of radon in natural gas at a home in Frederick, MD at approximately 30 pCi/L. This illustrates that the radon in natural gas is not a significant problem in homes. However, there is always a need for technology which allows the measurement of radon concentration in natural gas and in other gases for research and exploration.

Materials and methods

Figure (1) shows the basic equipment used as an accumulator with EIC units used for several applications, including the measurement of radon in water, measuring radon emanation rate from soil and building materials, and for calibrating EICs using NIST radon emanation standards. It consists of a wide-mouth glass jar with a screw cap and a rubber collar that can be tightened to make the unit leak-proof. Two EIC units can be accommodated inside the jar. One important application is to use it for basic calibration of EIC radon monitors (Kotrappa 1994). Knowing the emanation characteristics of NIST emanation standards, it is possible to calculate the expected radon concentration inside the jar after any desired accumulation period and compare this with the EIC measured average radon concentration. This is an air-tight system usable as an accumulator for different applications. The same unit is modified to serve as the system for sampling natural gas as shown in Figure (2). There are two valves which can be opened or closed. The natural gas line is connected through the inlet valve and is allowed to escape via the outlet valve. Once the sample is taken, the valves are closed. EICs measure the average radon concentration inside the jar after any length of retention. When used with NIST emanation standards EICs measure the accumulated average radon concentration. In the present work of determining the response factors for radon in natural gas, there is a need for the radon sources, which give higher emanations. Two NIST emanation radon standards were available with the following characteristics: Source 1 (SRM 4972), radium strength of 52.04 Bq (NIST-H), emanation coefficient 0.867, and Source 2 (SRM4971-34), radium strength of 5.082 Bq (NIST-L), emanation coefficient 0.891. These are fully described in Kotrappa (1994).

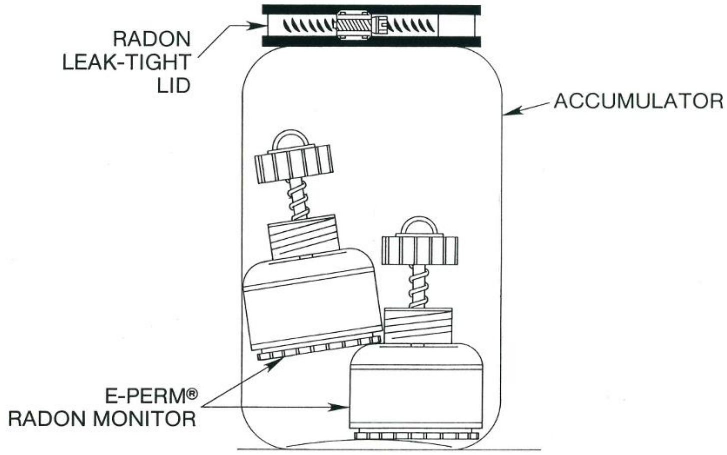

Figure (1): Standard accumulator used for calibrating EIC using NIST sources and other applications

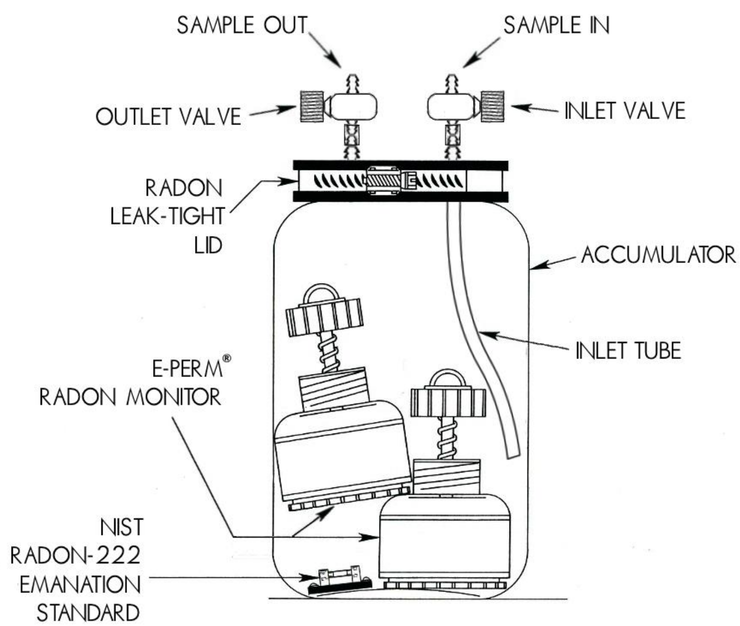

Figure (2): Accumulator system used for sampling natural gas with radon sources (NIST) standards or laboratory sources; for measuring radon in a sample of natural gas the standard source is not used

For some measurements the strength of these sources was not sufficient. Three additional radon sources were built using dry powder of uranium mill tailings. About 30 grams of such powder were loaded into a small pillbox, and the open end of the box was covered with Tyvek® [3] membrane and sealed to the edges of the pillbox. Tyvek® is known to fully transmit the radon emanated from the uranium mill tailings powder located inside the pillbox (Stieff 2012).

Three such sources (designated as 3, 4, and 5) were built. These sources can be used in place of the NIST sources where comparative measurements are needed. Figure (2) shows how the NIST sources are loaded into the sampling jar and can be replaced with the sources built in the laboratory.

Sampling system for measuring radon in natural gas using EICs

Figure (2) gives the schematic of the general sampling system for radon in natural gas using EICs with or without radon sources. NIST and laboratory sources are used for the experimental determination of *f* factors. The system consists of three parts:

1. A flow-through glass jar with two valves which can be sealed or opened.
2. A set of two premeasured SST (or SLT) EICs. Make sure that the EICs are in the "on" position.
3. A radon source when needed.

The procedure is as follows:
Record the <u>initial voltages of electrets</u> in both EICs.
Make sure that the natural gas stream has a flow rate of about 20 LPM (this provides sufficient volume changes to fully displace original air with the sampling gas).
Close the valves.
Connect the inlet valve to the stream of natural gas.
Open the inlet valve.
Open the outlet valve to the atmosphere.
Check for the flow by feeling (and smelling) the flow.
Continue to flow the natural gas for about 2 minutes.
Close the inlet valve.
Leave the outlet valve open for 15 seconds, then close the outlet valve.

Now the natural gas is locked inside the jar at atmospheric pressure. Because normally the stream is under pressure, this procedure eliminates possible higher than the atmospheric pressure in the analysis. <u>The sampling has ended.</u>

<u>After 1 to 3 days</u> unscrew the rubber collar and remove it from the jar. Unscrew the jar top. Take the EICs out and measure the <u>final voltages of both the electrets</u> in EICs.
Use a standard procedure to calculate the average radon concentration in air using initial and final voltages and the analysis time (1 day or any other chosen delay time).

(3) E. I duPont de Nemours and Company, 1007 Market Street, Wilmington, Delaware 19898

The results provide duplicate measurements of the average radon concentration in natural gas during the chosen delay period. What is needed is the initial radon concentration at the time of collection. This can be calculated using the procedure given in next section.

Equation for calculating the initial radon concentration (IRC) from the average radon concentration (ARC) as measured by EIC in sealed container for D days

The IRC is higher than the ARC due to the decay of radon over the measurement period. These two are related by equations (1) - (3). The ARC as measured by an EIC in a sealed container for D days is simply the time integrated radon concentration divided by duration, D.

$$ARC = \frac{TIC}{D} = IRC \int_0^D \exp\,(-\lambda\, t)\; dt \quad (1)$$

where TIC is the time integrated concentration in pCi-days/liter and λ is the decay constant of radon in day $^{-1}$ = 0.1814 day $^{-1}$.

$$ARC = \frac{(IRC)(1 - \exp(-\lambda D))}{(\lambda D)} \qquad (2)$$

$$IRC = \frac{(ARC \times \lambda\, D)}{1 - \exp(-\lambda\, D)} \quad (3)$$

Example: D = 3 days
ARC= 10 pCi/L
IRC = 12.97 pCi/L

Table (1) gives the calculated IRC values for different measurement periods and an ARC value of 10 pCi/L.

Sensitivity of the method

ΔV is the approximate voltage drop when the electret is used in an SST configuration. Sensitivity is defined as the radon concentration that gives a voltage drop of approximately 20 volts for the stated period, which corresponds to an error of roughly 10%. If a measurement period of 3 days is performed, the sensitivity will be around 3.3 pCi/L measurable with an error of 10%. For a measurement period of 1 day, the sensitivity is 10 pCi/L.

Table (1): Calculated IRC from ARC for different analysis periods and sensitivity analysis

Time Period (in Days)	Radon Decay Constant(day $^{-1}$)	ARC (pCi/L)	IRC (pCi/L)	Ratio	ΔV (for 10 pCi/L)	Sensitivity (pCi/L)
1	0.1814	10	10.93	1.093	20	10.0
2	0.1814	10	11.92	1.192	40	5.0
3	0.1814	10	12.97	1.297	60	3.3
4	0.1814	10	14.06	1.406	80	2.5
5	0.1814	10	15.21	1.521	100	2.0
6	0.1814	10	16.41	1.641	120	1.7
7	0.1814	10	17.66	1.766	140	1.4
8	0.1814	10	18.95	1.895	160	1.3
9	0.1814	10	20.29	2.029	180	1.1
10	0.1814	10	21.67	2.167	200	1.0

Experimental verification of leak tightness of the sampling system

The basic assumption made in the design of the sampling system is that the system is leak-tight over an extended period. This would allow the sampling system to analyze the samples at different measurement periods, as needed. Three samples were collected from the same source of natural gas and analyzed after 1, 4, and 8 days. From the measured average radon concentrations, initial radon concentrations were calculated by the method described above. The calculated results are given in Table (2). These results verify that the sampling system is radon leak-tight. Any measurement period between 1 and 8 days is acceptable.

Table (2): Initial radon concentrations from simultaneously sampled jars over time

Time Period (Days)	ARC (pCi/L)	Ratio	IRC (pCi/L)
1	25.5	1.093	27.8
4	21.2	1.406	29.8
8	13.8	1.895	26.2

Technical differences between scintillation cells and EICs

There are a number of differences between scintillation cells and EICs, which should be recognized throughout the study. They are delineated below.

Scintillation cells

The interior surface of the scintillation cell is coated with a layer of zinc sulfide, which serves as the scintillate. The gas to be measured flows through the inlet valve (and escapes via the outlet valve) for about two minutes, ensuring that sufficient air exchanges have occurred and completely displaced the original air in the cell. Immediately afterward, both the inlet and outlet valves are closed and the sampling is complete. After waiting four or more hours (in order to allow the radon decay products to attain equilibrium with the parent radon), an alpha count rate is measured and the resulting radon concentration is calculated. A correction is applied for the delay time between sampling and the beginning of the measurement when calculating the radon concentration. If the density of the measured gas is smaller than that of air, which is the case for natural gas (as it is rich in methane), more alpha particles strike the walls of the scintillation cell. This obviously increases the response of the cell for radon in natural gas relative to air. Likewise, if the density of the measured gas is larger than that of air (such as with carbon dioxide or propane), less alpha particles strike the walls of the scintillation cell. This decreases the response of the cell for radon in those gases relative to air. Correlating this property with changes in elevation also produces a similar but necessary correction factor. As gas density decreases at higher elevations more alpha particles strike the walls of the scintillation chamber relative to the same gas at sea level, necessitating a correction. This is portrayed below by Table (3). Density appears to be the only significant factor influencing the responses of scintillation cells.

Because the effective densities in natural gas can vary significantly from one source to another (due to its amalgam of various gases), experimentation is the only proper way to arrive at correct radon concentrations. Dr. Kitto has performed repeated measurements with scintillation cells, and has determined a factor of 1.07 as the over-response for scintillation cells for radon in natural gas relative to air, when measured at atmospheric pressure and room temperature.

Table (3): Specific gravities (taking density of air as 1.000) of gases

Name of Gas	Specific Gravity
Air at Sea Level	1.000
Methane	0.554
Natural Gas	0.60 to 0.70
Propane	1.522
Air at 500m Elevation	0.942
Air at 1000m Elevation	0.888
Air at 1500m Elevation	0.835
Air at 2000m Elevation	0.785
Table sourced from www.engineeringtoolbox.com	

<u>Electret Ion Chambers</u>

Electret Ion Chambers are quite different from scintillation cells, as shown in both their composition and methodology when measuring radon concentrations. Electret Ion Chambers measure the ion concentration within the gas; whereas, scintillation cells count the alpha particles reaching the zinc sulfide scintillate. As such, higher densities increase the response of radon in EICs, and lower densities decrease radon's response. This is inversely related to the response for scintillation cells. Also, SST EICs do not show significant effects of density differences (due to elevation) up to 4,000 feet (Kotrappa 1992). As natural gas is an amalgam of several gases as shown in Table (4), which are not in precise ratios to one another, this is only an approximated effect of the *W* value. As a note, it is worth defining the typical composition of natural gas, from Baltimore Gas and Electric Corporation given in Table (4).

Table (4): Composition of natural gas, reported from Baltimore Gas and Electric Corporation

Gas	Composition
Methane	93.32%
Ethane	4.65%
Propane	0.84%
Butane	0.18%
Nitrogen	1.01%

Due to the presence of so many factors, experimentation must be used to determine the actual response of electret ion chambers for natural gas and propane. This has been the goal of the present work. Another factor present in EICs (but absent from scintillation cells) is the ionization potential, which is defined by the *W* value (the energy in electron volts required to produce an ion pair). If the *W* value of the gas is lower than that of air, more ions are produced from the same alpha energy. This leads to an over-response of EICs, relative to the response in air, and is described in detail by Table (5). EICs are expected to give an over-response of approximately 1.15 due to the change in *W* value. Table (6) gives a summary of the distinguishing features between EICs and scintillation cells.

Table (5): *W* values for methane

Theoretical E (MeV)	From Table M/Air	*W* Value (methane relative to air)	Calculated Response in Methane
1.547	0.907	0.905	1.106
1.923	0.901	0.900	1.111
2.453	0.889	0.894	1.119
3.944*	0.879	0.877	1.141
4		0.876	1.141
5		0.865	1.157
6		0.853	1.172
7		0.842	1.188
8		0.830	1.205
Average			**1.150**

*Calculated *W* value is by extrapolation using fitted equation for the first four energies.
Gad Shani, Book, Radiation Dosimetry, Instrumentation and methods, CRC Press, Inc 1991, Boca Raton, Florida 33431. From Table 6 (RDIS) Page 25, Page 194 for correction from TE to air.

Table (6): Summary of differences in response between scintillation cells and EICs

Parameter	Scintillation cells	EICs
Increasing density or pressure	Decreases response	Increases response
Decreasing density or pressure	Increases response	Decreases response
Increasing *W* value	No effect reported	Decreases response
Decreasing *W* value	No effect reported	Increases response

Experimental methods for measurement of *f* for scintillation cells

The *f* factor is defined as the ratio of responses of radon in natural gas (using calibration constants for air) to that in air (using calibration factors in air).

<u>Dr. Kitto's method (2014) of measuring *f* factor for scintillation cells is illustrated below.</u>

Step 1. Radon-free air is bubbled through a NIST radium standard solution at a known flow rate and a sample is taken by scintillation cells and analyzed for radon concentration (designated as RnA).

Step 2. Radon-free natural gas is bubbled through NIST radium standard solution and a sample is taken by scintillation cells and analyzed for radon concentration (designated as RnG).

Step 3. All other conditions being the same, the *f* factor is calculated by taking the ratio between RnG and RnA.

Kitto concluded that the experimentally measured *f* factor is 1.07. This agrees well with the ratio of density of air to that of natural gas at atmospheric pressures and room temperatures.

Experimental method for measurement of *f* for electret ion chambers (EICs)

The principle used is similar to that used by Kitto, except for one noteworthy distinction: a radon source is used inside the sampling jar instead of bubbling the air through a radium solution. The radon source is simply a small pillbox containing about 30 grams of powdered uranium mill tailings. The top opening is covered with a Tyvek® sheet. The Tyvek sheet is sealed to the outside walls of the pillbox. This prevents the powdered uranium tailings from falling out. Radium-226 in the uranium mill tailings releases radon through the Tyvek® sheet, which is transparent to radon gas. This provides a continuous source of radon at a constant rate.

Step 1. Such a source is lowered into the sampling system (Figure 2). The valves are closed. The radon emanated from the source continues to accumulate inside the jar for a known length, such as three days. At the end of the three days the valves are opened. The sampling jar is also opened. The EICs are taken out and measured to calculate the average concentration of radon in the jar (designated as RnA).

Step 2. Leave the sampling system open for a day before starting this step. Repeat Step 1 with no radon source. The results are the background radon concentration in air (designated as RnABG).

Step 3. After venting the sampling system by keeping the jar open for one day, lower the same source and a new set of premeasured EICs. Collect the sample of natural gas using the protocol described in the above section on sampling the natural gas for measuring radon and collect the sample. Close the valves. At the end of 3 days the valves are opened. The sampling jar is also opened. The EICs are taken out and measured to calculate the average concentration of radon in the jar (designated as RnG).

Step 4. Repeat Step 3 with no source. The results are the background radon concentration in natural gas (designated as RnGBG).

With these measured radon concentrations, *f* is calculated using the following equation:

$$f = (RnG-RnGBG) / (RnA-RnABG) \quad (4)$$

Note that the natural gas used for EICs had a significant radon concentration, which has to be subtracted. On the other hand, Dr. Kitto used radon-free air and gas, so it is taken as negligible. The results of measuring *f* with EICs are listed in Table (7). The average is about 1.10.

Table (8) gives results of a similar experiment for the *f* value for radon in propane gas. Table (9) gives comparative results for the measurement of radon in natural gas using scintillation cells and using EICs, for samples collected on the same date. Note that calibration constants used are for air in both cases.

Table (7): Summary of 3-day experiments: radon in natural gas and radon in air

Grand Summary of 3-day experiments			Net
Source#	Net Radon in gas (pCi/L)	Net Radon in air (pCi/L)	Gas/air (*f*)
3	155	142	1.092
4	166	154	1.078
5	160	146	1.096
6 (NIST H)	76	69	1.101
6 (NIST H)	75	66	1.136
6 (NIST H)	75	67	1.119
3	155	143	1.084
3	153	141	1.085
		Average	1.099
		STDEV	0.020

Table (8): Summary of 3-day experiments: radon in propane gas and radon in air

Radon Source #	Net Radon concentration in propane gas (pCi/L)	Net Radon concentration in air (pCi/L)	Ratio of radon in propane to radon in air (pCi/L)
NIST-L	11.5	8.5	1.353
NIST-L	11.7	8.5	1.376
NIST-H	92.9	68.9	1.348
		Average	1.359

Table (9): Comparative results from scintillation cells and EIC, samples collected on the same date using calibration constants for air.

Collection Date	Sample Number	Scintillation cell (pCi/L)	EIC (pCi/L)
May 4, 2015	1	28.4 ± 2.2	28.1 ± 2.0
	2	27.4 ± 1.6	27.0 ± 1.9
	3	27.4 ± 1.7	26.9 ± 1.8
	4	n/a	26.5 ± 1.9
	Mean	**27.7**	**27.1**
June 16, 2015	1	27.0 ± 1.4	27.0 ± 1.9
	2	27.9 ± 1.5	26.1 ± 1.9
	3	27.3 ± 1.6	26.3 ± 1.8
	4	26.4 ± 1.8	27.2 ± 1.9
	Mean	**27.2**	**26.7**
June 29, 2015	1	28.8 ± 0.9	28.7 ± 2.0
	2	29.7 ± 1.0	31.9 ± 2.2
	3	28.4 ± 0.9	29.9 ± 2.1
	4	29.3 ± 0.9	28.5 ± 2.0
	Mean	**29.1**	**29.8**
To calculate corrected radon concentration, results of scintillation cells need to be divided by 1.07 for results obtained by scintillation cells and to be divided by 1.10 for results obtained by EICs.			

Results and Discussion

The *f* value for scintillation cells is 1.07 and for EICs is 1.10 as shown in Table (7). These are only slightly different from each other. Accuracies appear to be similar in both cases.

Table (8) gives the *f* value for measuring radon in propane gas. The measured *f* value is 1.38; whereas, it should have been 1.5 if due only to the difference in densities. Such differences can be accounted for the differences in W values and other unknown parameters. Normally propane gas used as a cooking gas does not contain radon because propane is produced by distillation of crude oil. This simply illustrates that the methodology used in this work can be used for arriving at *f* values for measuring radon in other gases, if required.

Table (9) gives comparative results from the measurement of radon in natural gas as measured by scintillation cells and as measured by EICs. Samples are taken at the same location and on the same date and time. Calibration constants used are for air at atmospheric pressure and at room temperature. The results are in good agreement between each other and accuracies are also similar. To be more accurate, results need to be divided by 1.07 for scintillation cell results and results of EICs need to be divided by 1.10.

Recently there was an inquiry whether EIC-based radon flux monitors (used for uranium exploration work) can be used at certain locations where radon is accompanied with natural gas from the ground. Based on the current work the authors can confidently say that the calibration constants for air can continue to be used in such situations, because a small concentration of natural gas in the sample will not significantly affect the measurement.

Scintillation cells have an advantage in that multiple measurements can be done on a single sample; whereas, the analysis can be done only once for each EIC collected sample. Multiple samples need to be collected if more than one measurement is required.

Acknowledgement

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EFFECT OF SUB-SLAB PRESSURIZATION ON INDOOR BASEMENT TEMPERATURE AND RELATIVE HUMIDITY

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Abstract

Pressurization as a mitigation strategy in radon mitigation is mentioned in training courses but is not widely practiced. Allied Radon Services, Inc. has encountered a house in which portions of the top of the foundation and sill plate are below grade. It is believed that radon is being drawn into the basement through the sill plate/foundation joint. By pressurizing the basement slab with two systems, the radon level is reduced to an average between 2.0 and 3.0 pCi/L. In order to determine the effect that pressurizing the slab has on indoor temperature and relative humidity, data loggers have been deployed. One is measuring conditions outdoors; two are measuring conditions at communication test holes in the slab; and the fourth is measuring conditions in the basement. This data will assist in determining whether it is necessary to take precautions to protect the indoor environment of the house.

Introduction

The house which is the subject of this paper is one that would be considered to be a very normal mitigation project. The house is approximately 30 years old. It is a two-story brick veneer frame house with a poured basement that is 75% finished. There is a sump pump that has been added after construction with a bolted down cover; a slab on grade Sun Room on the rear of the house; an attached garage; and an in-ground pool in the back yard with brick pavers between the house and the pool. The house has a high efficiency furnace that did not have a source of exterior makeup air and was pulling makeup air from the basement. The basement has one exit door and no basement windows. The initial radon level was 6.7 pCi/L

(1) The author acknowledges the assistance of J Kevin Roth, AIA, NCARB, CSI-CCS for collaboration and assistance with data collection and analysis on this project.

An exterior picture of the house is shown in Figure (1).

Figure (1) Exterior Picture of house.

Methodology

The initial mitigation strategy was to install a single suction point sub-slab depressurization system routed through the garage with an RP140 fan in the garage attic and discharge through the garage roof. The bolted down sump cover was replaced with a gasketed cover that had a site glass. Caulk was applied to the wall/floor joint, to the extent possible. Subsequent testing revealed that the radon level was still greater than 4.0 pCi/L.

The following unsuccessful adjustments were then made to the mitigation system.

- Fan: The fan was upgraded to an RP145. Diagnostics indicated that communication did not readily extend across the slab.
- Suction points: Suction points were added to the garage and sunroom slabs.
- Suction points: Three additional basement slab suction points were added.
    - When adding additional suction points in the basement, it was discovered that the center of the basement slab was sitting on sandstone.
- Exterior makeup air for furnace was added.
- A second system.
    - When adding the second system, it was discovered that portions of the sill plate were below grade. Even though the basement was not under substantial negative pressure to the atmosphere, with the basement having no windows, the house was apparently drawing makeup air through portions of the sill plate joint that was below grade. As a result, the house was effectively mining radon around the foundation.

Even with two systems and six suction points, the radon level remained above 4.0 pCi/L.

At this point, the decision was made to reverse the fans and pressurize the slab. This house is located in Southern Illinois which can have some zero degree Fahrenheit days in the winter. The concern was the impact that pressurizing the slab would have on inside temperature and humidity.

In order to measure that impact on temperature and relative humidity, four data loggers were deployed. One measured data outdoors; one measured data in the basement; and the other two measured data directly above two communication test holes in the basement floor.

The closet data collection point was approximately 10 feet from the system pressurization point and the bench data collection point was approximately 20 feet from the other system pressurization point. Data was gathered from December 19, 2014 through February 9, 2015. The data loggers were set to record data at five minute intervals resulting in 15,027 data points each for temperature and % relative humidity per data logger.

Pressurization of the slab resulted in reducing the radon levels to below 4.0 pCi/L. Tests ranged from 2.2 pCi/L to 3.6 pCi/L.

The maximum and minimum temperature, % relative humidity, and dew points are shown in Figure 2.

	Data Ranges			
	Basement	Bench	Closet	Outside
Max Temp	66	62	60	63
Min Temp	59	58	52	5
Max % RH	70.5	100	100	98.5
Min % RH	33.5	100	100	44
Max Dew Point	52.4	64.3	61.9	52.6
Min Dew Point	31.3	58.1	53.5	-2.6

Figure (2) Data Ranges

Pressurization did have some impact on basement temperature. While exterior temperatures ranged from a high of 63 F to a low of 5 F, basement temperatures ranged from a high of 66 F to a low of 59 F. Basement temperatures generally correlate to outside temperatures. It is felt that the closet data logger temperatures tended to be less than the other interior data logger readings because the data logger was located approximately 10 feet from the pressurization point versus approximately 20 feet for the other data logger. A graph of the basement temperature data is shown in Figure (3). Figure (4) displays the temperature comparisons of all data points.

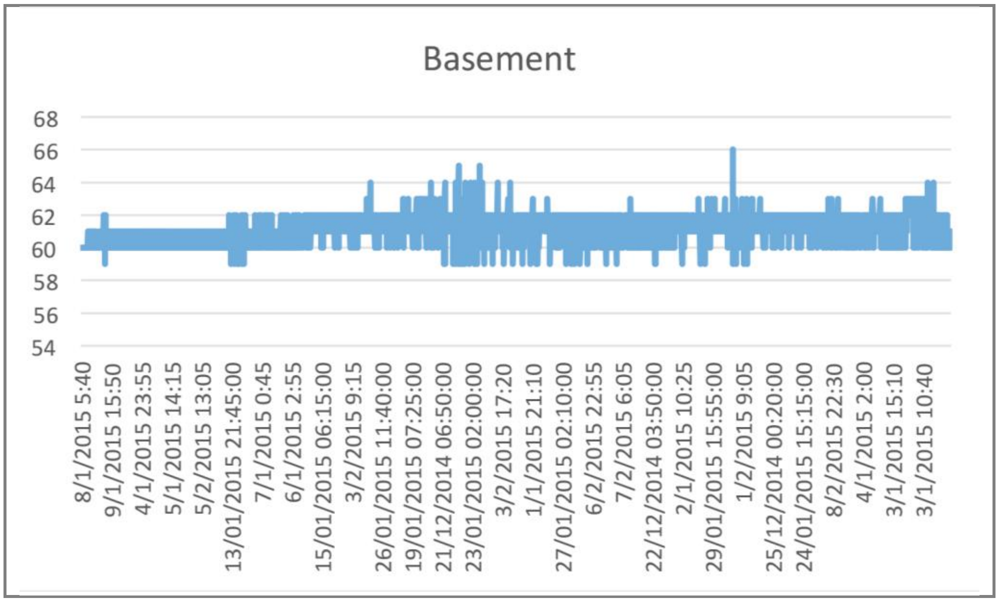

Figure (3) Basement Temperature

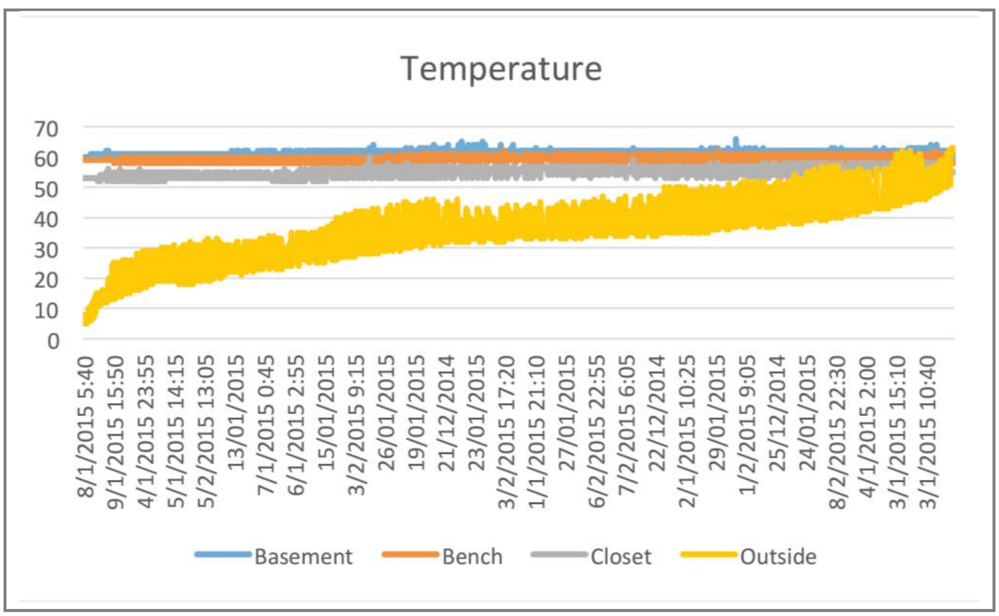

Figure (4) Temperature data

Pressurization of the subslab had a definite impact on relative humidity levels in the basement. Initially, relative humidity levels were in the 35% range. By the end of the data collection period, relative humidity levels were consistently in the 55% range. A graph of basement % relative humidly is displayed in Figure (5).

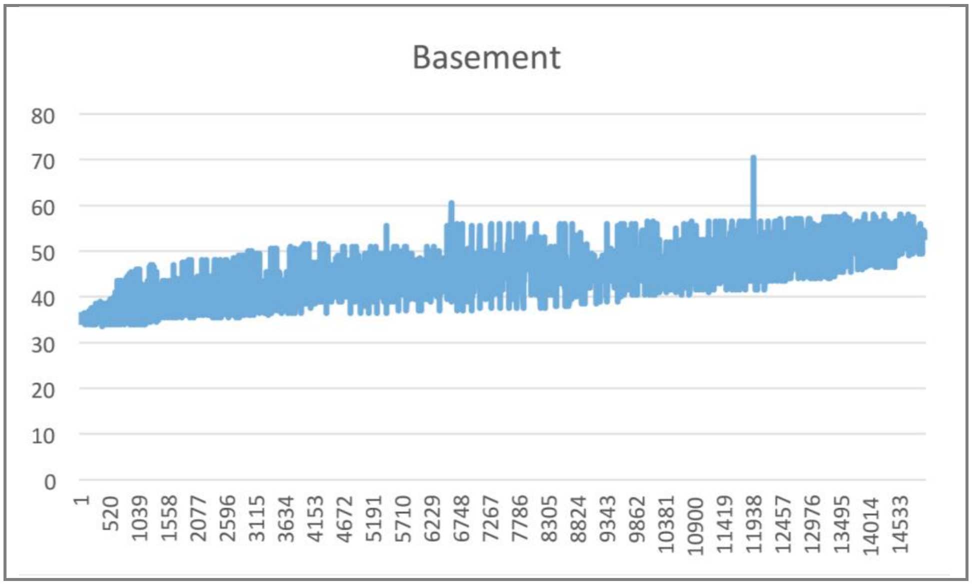

Figure (5) Basement humidity

Mitigation systems utilizing subslab depressurization over time tend to decrease the humidity level beneath the slab. In the case of pressurizing the slab, the % relative humidity at both communication test holes consistently displayed 100%. For some reason, the data loggers recorded % relative humidity at the test holes in excess of 100%. A graph showing % relative humidity in the basement, at both test holes, and in the exterior atmosphere is shown in Figure (6).

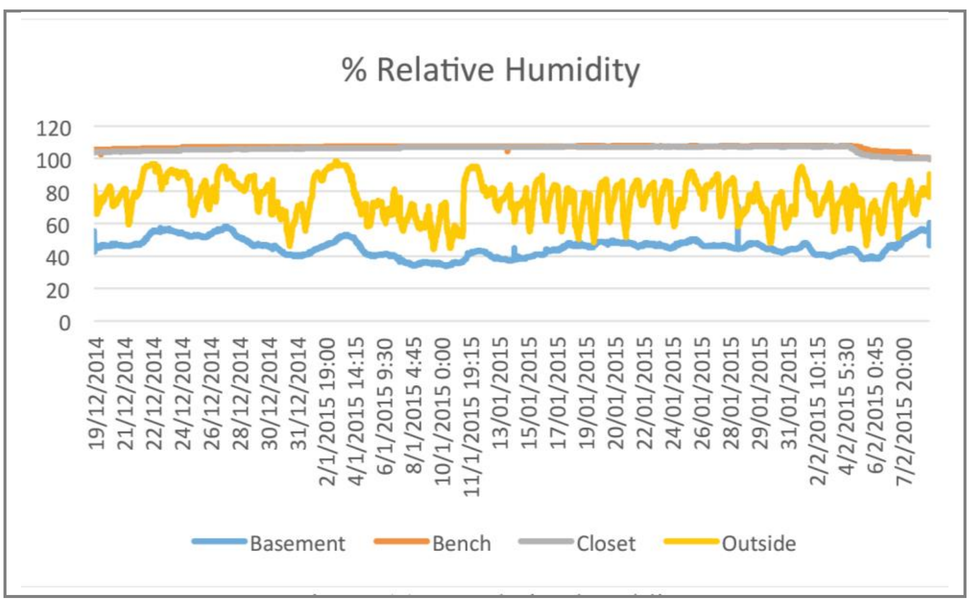

Figure (6) % Relative humidity

The data loggers also calculated dew point. At the beginning of the data collection period, dew point in the basement was 32 degrees F. As % relative humidity rose during the collection period, dew point increased to 43 degrees F. A display of basement dew point is displayed in Figure (7) and a comparison of basement, test holes and exterior dew points is shown in Figure (8).

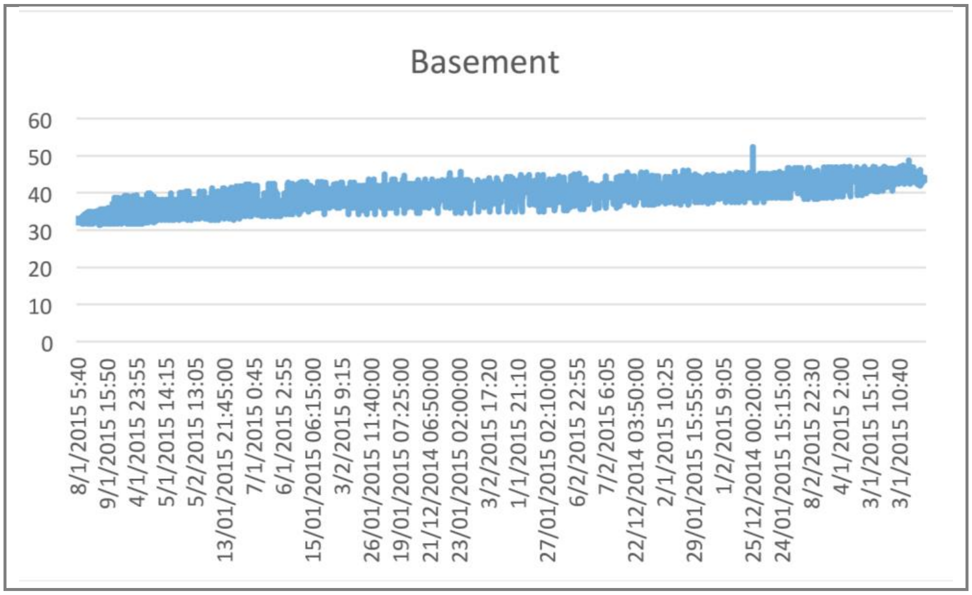

Figure (7) Basement Dew Point

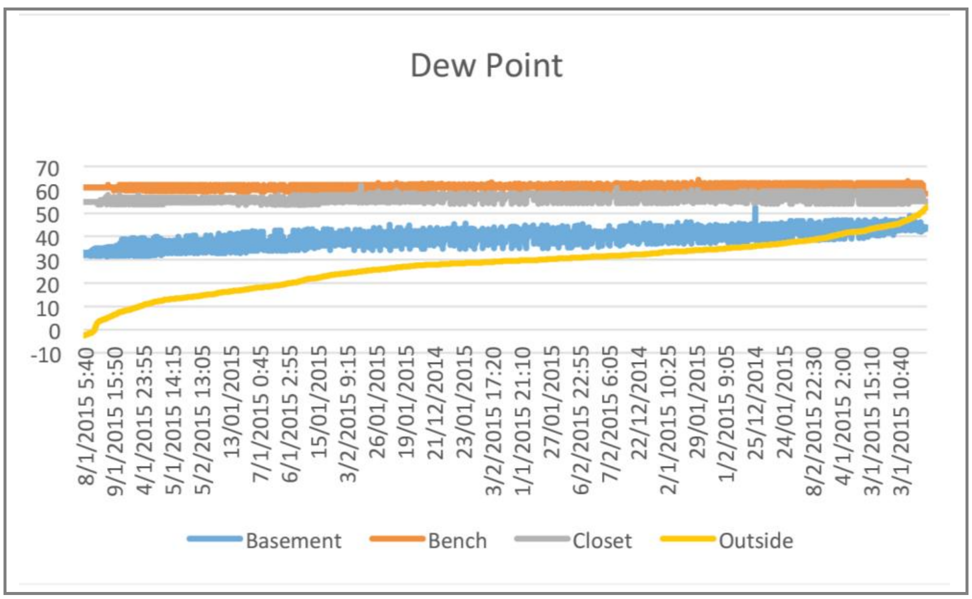

Figure (8) Dew Points At Multiple Locations

Pressurization of the slab did result in a very severe derogation for the smell of the air in the basement. The objectionable smell in the basement rendered pressurization, as a strategy, not a viable option. The interesting observation was that when the fans were reversed and the slab was depressurized, there was an immediate improvement in the smell of the air in the basement.

The radon at the house was finally mitigated by depressurizing the slab with two systems. One system has a RP 140 fan and the other has a RP145 fan. In order to obtain makeup air, the blower on the high efficiency air handler is being run continuously.

Testing using activated charcoal test kits indicated the following levels throughout the house from April 1, 2015 through April 6, 2015.

Basement	0.9 pCi/L
First floor	0.8 pCi/L
Second floor	0.6 pCi/L

Conclusion

Subslab pressurization may result in reducing radon levels to less than 4.0 pCi/L. Based on this house, pressurizing the slab will impact basement temperature and relative humidity levels in the basement will increase dramatically which may create other issues.

MEASUREMENT OF RADON LEVELS IN CAVES: LOGISTICAL HURDLES AND SOLUTIONS

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Abstract

Currently, the caves in Northeastern Iowa are the subject of a number of ongoing radon studies. Because cave temperatures tend to be fairly uniform and mirror the mean year-round surface temperature above the cave, a similarity exists with homes with a basement or cellar. However, although thermally similar, caves tend to have higher relative humidity, typically exceeding 90 percent, and also have an extremely heavy burden of particulate aerosol matter consisting mostly of water droplets and earth. Another difference is access, cave entrances can be located in remote, hard to reach areas. Once inside the cave, the radon tester is faced with the challenges of climbing, passing through small openings and the prospect of having to swim with the radon equipment to reach the desired test location. This presentation reports the performance of the radon monitoring equipment in this environment, and details special transport and deployment techniques that were adapted to ensure acceptable data integrity.

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Introduction

Caves have been intertwined with human culture since times of antiquity, serving as sites for religious ceremonies, burials, residences, recreation, and scientific study. All 50 US states have multiple recorded caves (Culver, 1999), mainly solutional in nature but also including volcanic, wave-cut, stream-cut, shelter, framework, crevice, talus, sea, and glacial caves (Palmer, 2007). Depending upon the locally defined definition of what constitutes a cave, they can vary in size from 15-50 feet in length and some can exceed hundreds of miles of mapped passages underlying large surface areas. In the US, karst cave networks are the most common and are caused by the dissolution of limestone by ground water. Areas with limestone formations that exhibit karst features (not all types of limestones will exhibit karst degradation) can have a high density of caves and their presence can significantly alter the local environment with the presence of sink hole, and in some cases the absence of surface water (Moore, 1978).

Chemically, limestone is described in the literature as calcium carbonate, and it, along with other carbonate minerals, has been described as among the least uraniferous substances in the earth's crust (Bell, 1963). A more recent measure pegged the mean uranium concentration in limestone at 2 parts per million (ppm), which is only slightly below the 2.8 ppm expectation for the entire earth's crust (Ayotte, 2007). However, natural limestone bedrock units are notoriously impure. The presence of phosphates and shale in the limestone unit often lead to uranium levels much higher than the expected pure limestone mean (Angino, 1964). It has been noted that the karst limestone in the Bighorn Mountains of Montana is relatively rich in uranium content, although this is largely due to secondary deposition, where the uranium has been leached from elsewhere and then transported and deposited on the limestone surfaces in an epigenetic manner (Bell, 1963). Another method deposition involves the leaching and concentration of uranium from glacial drift in a southwestern Ohio limestone region (Gall, 1995). Limestones tend to have minimal thorium content, however do contain radium (226) in equilibrium with uranium (238) (Cothern, 1990).

The presence of uranium in either the limestone bedrock or in secondary deposits on the surface of subterranean limestone ensures that radon will be formed and potentially vented into local cave atmospheres. Numerous studies have looked at subterranean radon concentration using a variety of monitoring devices: the radon activity found in caves throughout the world varies widely (Cigna, 2003) and does not show clustering around a calculated mean. Compared to the upper limit of what would be acceptable for a place of residence, cave radon concentrations tend to be much higher. Espinosa reported radon activity in the 25.8 – 133.3 picoCurie per liter (pCi/L) range using track etch detectors in several Mexican caves (Espinosa, 2008). Continuous radon monitors have been used to measure radon levels of 27 – 225 pCi/L in a Czech Republic show (commercial or tourist) cave (Rovenska, 2010) and over 600 pCi/L in a show cave in Minnesota (Lively, 1995). Despite these high values, the touted risk to show cave patrons or recreational cavers is thought to be small (Field, 2007) due to the relatively small time of exposure. The greatest cave radon safety concern is for employees who have job duties leading to much greater time of exposure, such as show-cave guides (Aley, 2006) or outdoor recreation trainers (Langridge, 2010).

In addition to safety concerns, it should be emphasized from a more holistic perspective that in some ways, caves present an ideal laboratory to study radon movement between its creation and subsequent penetration into human dwellings. A poor correlation between soil gas radon levels and bedrock uranium and radium has been noted, with exceptions at the two extremes of bedrock actinide element concentration; the uncertainty in transport being the wild card (Cothern, 1987). Caves permit entry into the mysterious transport domain, and allow scientific experimentation to characterize the movement of radon and what factors impact it.

The two primary cave locations for this study are both in northeastern Iowa, residing in what has been defined geologically as the Galena Cuesta of the Ordovician era (Palmer, 2009). The general region is sometimes referred to as the Driftless Area, denoting that the area was missed by the most recent glaciation that covered most of Iowa, Wisconsin, and Minnesota. Entrances to each cave reside on private land and are gated which provides the controlled access required for scientific study. Coldwater Cave, in northwestern Winneshiek County, is an underground river system that has an excess of 17 miles of surveyed passage (Coldwater Cave Project, 2003). It is classified as an active fluviokarst system, where the cave river is perched on an insoluble layer and fed by water from perennial springs along with surface sinkholes and swallets (Palmer, 2009). Kemling Cave is a rectilinear maze cave with significant joint control that is a member of the “spar caves” that have been mined for lead and zinc in southeastern Dubuque County (Palmer, 2009). It has ca. 2.1 miles of mapped passage at present (Klausner, 2015).

The challenges involved in measuring radon in these caves were anticipated. In contrast to most cave radon measurements reported to date, neither of the study caves has been commercialized, resulting in more challenging terrain and transport requirements for sensors. The predicted temperature for a cave is approximately the mean annual temperature on the surface above (Palmer, 2007). Air temperatures in Coldwater Cave have been measured in the 8.6 - 9.5 ^{o}C range (Koch, 1974), with Kemling expected to be slightly warmer due to its more southerly position. While less than room temperature, it was similar to the “cellar temperatures” one might anticipate finding in home basements, and would be within the working range of most radon sensors. However, unlike cellars, the driest of caves exceed 90% relative humidity, with most approaching 100%. Published relative humidity measurements in Coldwater were predominantly off the scale of the measuring equipment (Koch, 1974). Both caves have active drips and puddles, and Coldwater also has active stream flow which requires swimming in places, making a wetsuit standard in-cave apparel. Therefore sensors that are designed for indoor usage are probably going to be outside the recommended manufactures humidity and moisture maximum specification. Dirt, mud, and passage size restrictions are also standard features of cave passages outside of tourist trails. Mud and dirt are unlikely to accumulate during sensor operation, but build-up during transport of the sensors to their in-cave operation positions could easily threaten sensor operation. When a caver is forced to crawl or squeeze through a passage restriction, the sensors being transported will likely be jostled and bumped much more vigorously than a device kept in a mounted backpack. Both of the study caves have reputations for being hard on equipment designed for use in caves; sensors designed for indoor operation would seem even more vulnerable. The interior atmosphere varies greatly from cave to cave, but many have been observed to contain a very heavy particulate burden, which could potentially clog the intake mechanisms or short electronic circuits on radon monitors. Neither cave has electrical power, so the monitor must be able to function on battery power for the duration of the measurement.

The objective of this study is to correlate cave radon concentration with environmental factors. This report details methods adopted and lessons learned while acquiring data from continuous radon monitors in the two study caves.

Materials

Measurement of radon activity was achieved with Radon Scout [RS] or Radon Scout Plus [RSP] continuous Radon monitors and Radon Vision software (Rad Elec). Each of the Scout types relied on diffusion to bring gaseous samples into the unit, with subsequent measurement of alpha radiation via a silicon semiconductor detector. The dual requirement of being gaseous and an alpha emitter provided selectivity for radon detection, although some signal contribution from alpha-emitting radon daughter elements was expected. Independent measurements of pressure, temperature, and relative humidity were made using OM-CP-PRHTEMP101 [PRHTEMP] sensors with OM-CP Data Logging software (OMEGA Engineering). For the PRHTEMP, the pressure sensor was piezoresistive, the temperature sensor was a thermistor-type precision RTD element, and the humidity sensor was a capacitive polymer style which, it should be noted, has an upper limit specification of 95% RH. The tablet computer used was a Venue 11 Pro 7130 (Dell). Cases for the tablet included a Pelican 1085 Case (Pelican Products) and a Rugged Max Pro Case (Targus). Desiccant cartridges were 1500D Peli Desiccant units containing 40 grams of anhydrous silica gel in a porous metal case (Grainger). Tyvek® envelopes were from DuPont, plastic bags were of the Ziploc® make, and the kayaking dry bag was a model 163OP-CLR from Outdoor Products.

Results and Discussion

Given the research goal of measuring radon within cave environments, it was crucial to find monitoring equipment that could function in high humidity and on battery power. One Radon Scout and one Radon Scout Plus continuous radon monitor were originally purchased based upon vendor assurances that they were rugged and would function in conditions up to 95% relative humidity. It was also anticipated that the instruments would be required to operate beyond this humidity value, and that there would be some exposure to water in the condensed phase in addition to dust and mud. The technical specifications for both sensors, as given in the user's manual (Rad-Elec, 2010), do not list a humidity operating range, although it does note that the internal sensor for relative humidity produces output values from 0 to 100% RH. Another notable find within the user's manual, under the heading of "Important Care Instructions" for the Radon Scout Plus, was the statement, "DO NOT shake, drop, toss, turn upside-down, or handle the device in any type of "rough" manner." When transporting the RS/RSP through cave passages involving crawling, climbing, or other contortions, it was expected that this recommendation would be exceeded in practice as well.

Many of the field trials with the RS/RSP instruments involved both units operating at the same time but at differing spots in a cave. Early trials revealed two issues regarding the output data. First, when operating in the short term data collection mode with 1-hour intervals between collections, the RS would record the first line of data at time zero immediately after it had been started, whereas the RSP would record its first line of data one hour after the start of the unit. The first RS point was discarded as a result. Further review of the data sets from the RS/RSP units showed low and rising values for the initial radon activity readings. The RSP user's manual (Rad-Elec, 2010) cited a response time specification of 120 minutes to reach 95% of the final value. In light of this information and the observed sensor behavior, it became standard practice to omit from calculations any readings collected during the first 3 hours after activation of the probe.

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The Radon Scout Plus (RSP) weathered more than 20 in-cave trials before any evidence of a glitch or data error was observed. However the Radon Scout (RS) collected a single in-cave trial of 25 hours in duration before starting to suffer problems in subsequent trials (Table 1). For the second in-cave trial of the RS, both it and the RSP were placed in the same cave at locations about 100 meters apart. Both worked well for the first 82 hours, at which point the radon activity measured by the RS dropped to a value of zero and remained that way for the balance of the trial. The RSP continued proper operation throughout the trial, and it was noted that the only function of the RS that failed was the radon measurement. The other parameters measured by the RS, temperature and relative humidity, proceeded unaltered after the radon measurement went to zero. Prior to the RS glitch, the radon activity as a function of time was showing similar behavior at both locations with the two different radon sensors with a correlation coefficient of 0.9508 from the two parallel data sets. Subsequent field trials of the RS suffered the same error, although typically it occurred more quickly following initialization, minimizing any conclusions that could be derived from the data sets. Eventually, the old RS was exchanged for a newer version. Table (1) shows the outcome, with the new RS worked well for 3 short trials, but then once again lapsing into the same behavior as the prior unit, with the radon measurement going to zero and the other parameters continuing to function. After several frustrating trials with the RS, and a track record of success with our RSP, we upgraded the RS for a second RSP.

Special precautions and procedures were adapted when the RSP units were deployed in caves to minimize shock or environmental exposure to the sensor. When the original RSP was purchased, a thermoplastic case was an optional accessory. The case did not provide a hermetic seal, but instead was vented via large openings to allow the RSP to collect data while inside the case. The value of the case in protecting the sensor during in-cave transport quickly became evident, and case transport and operation became an accepted standard procedure. To provide additional shock protection, the thermoplastic case was swaddled in a beach towel prior to placing it in a cave pack for transport. In “wet” caves where one could reasonably expect water to penetrate into the cave pack containing the RSP, the sensor, while inside the case, would first be sealed in a 2-gallon Ziploc® bag and then further sealed inside of a suitably-sized kayaking dry bag prior to being placed inside the cave pack. The entire package would typically fit into a large cave pack along with the other requisite supplies needed to support such a cave trip, although there was usually not much room for additional scientific supplies in the pack. Therefore an experiment needing additional equipment would require either multiple trips or multiple people for transport.

Some in-cave sampling locales were equipped with nice ledges and dry shelves on which to perch the RSP. At other times, when the cave floor was wet or muddy, the ground uneven, or when precise vertical positioning of the sensor was sought, a modified photographic tripod was utilized. The tripod modification consisted of removing the camera mount and threading a ½ inch diameter Schedule 80 PVC pipe segment into the tripod. By using pipe unions in conjunction with different lengths of PVC, the height of the mounting point for the RSP could be varied. The actual mounting was done by drilling holes and threading eyebolts through the PVC that were anchored with wing nuts because standard nuts were found to be unwieldy for operation in the cave. A large locking carabiner could then clip into the eye of the bolt and then around the handle of the thermoplastic case for the RSP.

The tripod mount resulted in an RSP configuration where the sensor was rolled 90 degrees onto its side (hereafter referred to as vertical). The RSP user's manual (Rad-Elec, 2010) does not give any specific advice regarding the orientation of the unit during data collection, but all depictions of the sensor show it placed horizontally and the aforementioned warning about not turning the unit upside-down suggested that this might be an issue. Conversations with Rad-Elec representatives revealed that they felt the unit could function properly in this orientation based on some tests they had run. Wanting to be certain, a trial was configured to evaluate whether the response was independent from RSP orientation. Since the two RSP's in the study had slightly different sensitivities, an in-cave normalization trial of the two sensors side-by-side in identical orientations can be seen in Figure (1a). Figure (1b) shows a different trial of the same two RSP units, side-by-side in Coldwater Cave, one mounted horizontally and one vertically. The two traces in Figure (1b) closely track one another, and the offset in detector response is nearly identical to the normalization trial, allowing the conclusion to be made that the vertical mounting does not differ in RSP radon activity response compared to the standard horizontal mount.

The fully-deployed RSP with tripod mounting could be top-heavy, particularly when the RSP was supplemented with other sensors placed on the same tripod. Experience determined that it was important to keep the eye of the eyebolts as close as possible to the PVC pipe to minimize the lever arm of the RSP mount and maintain stability of the apparatus. When the tripod base was in an active watercourse or potential watercourse in the case of precipitation, or if the in-cave site was inhabited by wildlife of significant size (raccoons in particular), it was judged prudent to weigh down the tripod base to ensure it would not be tipped during the experiment. Loose stones were the weight of choice, but in several instances bricks or barbell weights were used in this role when loose stones were unavailable and the weights didn't need to be carried for some distance.

For protection from water and excessive humidity, the RSP units were always packaged in Tyvek® envelopes for in-cave data collection. The sensor could be placed in a 10 X 15 inch mailing envelope, with the excess then folded over neatly permitting it to still fit into the foam cutout of the thermoplastic case and then sealed properly. Prior work demonstrated (Stieff, 2012) that Tyvek® is transparent to Radon. The cited study largely utilized radon chambers that had fairly stable radon activities and sensors that produced integrated average measurements. Typically, the caves of the current study have higher radon activities and much greater variability as a function of time than this prior work. Therefore a determination was needed to see if Tyvek® radon transparency extend to higher concentrations, and if the barrier would cause a kinetic lag in the diffusion rate of radon into the unit. Figure (1c) shows a side-by-side comparison collected in Kemling Cave of two RSP units with and without Tyvek®. The RSP units are the same ones used in the study shown in Figure (1a), so the normalization factor from this trial can be applied to Figure (1c). Ultimately, the sans-barrier RSP in Figure (1c) differed from the with-barrier data by nearly the same factor as for the normalization trial; so no evidence of a lack of transparency can be seen. In terms of a potential time lag, the correlation coefficient of the traces in Figure (1c) is 0.9946, and when the with-Tyvek® sets are offset forward in time by one and two hours relative to the without-Tyvek® set, the coefficients drop to 0.9818 and 0.9375 respectively. No kinetic lag can be seen; if one were present, it was less than the sampling interval of the device. Therefore it was concluded that protecting the RSP with Tyvek® had no measureable impact on the in-cave radon measurements.

In addition to measuring radon activity, the RSP also acquired temperature, pressure, and relative humidity data; the correlation of these values with the radon activity is important for ongoing research in this group. Given that the caves were cooler than room temperature and that the Tyvek® envelope encased an electronic device that presumably produced heat, there was a concern that the Tyvek®-encased RSP would produce inflated temperature readings while in the cave. As well, the Tyvek® envelopes were touted as being transparent to water vapor, but their hydrophobicity suggested that a Tyvek®-encapsulated RSP might read an artificially low relative humidity, or at least have a time lag as the water vapor was slowed traversing the pores of the envelope. From the same trial as Figure (1c) with an RSP with and without Tyvek® encapsulation, the data given in Figures (2a) through (2c) were recorded. Supplementing the RSP data, two dedicated temperature-pressure-relative humidity sensors, the PRHTEMP101 models, were run concurrently, one in Tyvek® and one without. Figure (2a) shows the temperature response of the 4 sensors while in Kemling Cave. Although the temperature separation between the RSP units initially looks to be significant, a close look reveals that they are largely separated by a single minimum data increment caused by the analog to digital converter. The PRHTEMP in Tyvek was actually a new-and-improved version of its counterpart, and its smaller digital increment led to the smoother output trace when compared to its complement. Also the PRHTEMP units provided a more precise output than the RSP units. Nothing in Figure (2a) can be interpreted as suggesting that the envelope artificially inflated the measured temperatures, nor had any significant impact on the measured temperature. Figure (2b) displays the pressure overlay from all 4 sensors; and it also shows no evidence of impact from the Tyvek® envelope. Again, the PRHTEMP sensors have smaller digital increments and therefore greater precision than the RSP pressure data. Finally, Figure (2c) shows the relative humidity overlay from the 4 sensors. Given that the cave humidity is expected to be very high yet relatively constant in the absence of air temperature change (Palmer, 2007), none of the sensors appear to be yielding trustworthy output in the time frame displayed. It does appear that the RSP in Tyvek® produces humidity data that lags behind the unencapsulated model, but the PRHTemp units portray just the opposite behavior, so the observed differences seem unlikely to be due to the Tyvek® envelopes. The general shapes of the humidity vs. time plots in Figure (2c) are typical of those collected in other trials.

An examination of relative humidity response for other, longer, in-cave collections with Tyvek®-encased RSP units is presented in Figure (3). Although from different caves and different sampling sites, the plot suggests that even after experimental durations of 200 hours that the relative humidity readings are not fully stabilized and will underestimate the true humidity value, and that the actual humidity is likely in the 97-100% range for these locations. Insufficient long-term PRHTEMP in-cave data was available to compare the different detectors in this same time frame.

As noted earlier, the Radon Scout Plus units completed more than 20 in-cave trials without a perceptible error. However, during that time span two non-cave trials suffered duplicate data errors where the first sampling date was incorrectly recorded as Jan 1, 2000 and the start time within a few minutes of midnight. Since the time increments remained consistent, careful record keeping of sensor start and finish times made these correctable errors, but their presence nevertheless caused concern. Conversations with the vendor led to the suggestion that efforts be made to limit jostling of the installed D cell batteries following software initialization. There was no published work addressing this issue, but it had been observed in other situations. This also was consistent with the requests in the RSP User's Manual (Rad Elec, 2010) that when installing batteries, the process should be done "gently" by sliding them in horizontally rather than dropping them in vertically. In response to information about the battery-jostle concern, surface travel to subsequent cave sampling locations was done with the RSP battery chamber empty. The batteries were installed on the surface prior to entering the cave, and the software initialization done with a laptop computer at this time. This procedure seemed to help, but as sampling sites required longer and more arduous transport of the RSP inside the caves, the glitch with the clock reset reappeared. Finally, after one particularly difficult carry, the RSP would not allow data download until the batteries were removed and reinstalled, at which point the collected data could be accessed. The recovered data set did feature the correctable date/time reset, but was otherwise free from error.

Since further deep-cave experiments were of interest, the battery-jostle problem became a key concern. The deep-cave measurements required significant preparations and investment of time to get the monitors to the desired location. If the data were lost, it would require months to perform a second measurement. Because the battery-jostle was largely an issue during monitor transport from the entry of the cave to the sampling site, it was decided to set the RSP up once at the sample site. To accomplish this, a table computer equipped with a USB port was also transported to the sampling site as well. The tablet computer was then used to initialize the RSP at the sample site thus eliminating the potential data loss from battery-jostle during transport.

The new RSP initialization procedure was not without some challenges as well. First the added logistics of transporting a tablet computer and its interface cable a long distances though a wet, tight access cave had to be developed. The computer came with a Rugged Max Pro case that was designed to cushion it from bumps and eliminate screen damage, but did not provide a waterproof seal. The computer was kept in this case at all times, as it could be operated in the case, and the USB port could be engaged via an access flap. After packing in this case, the entire tablet was then placed inside a 2-gallon Ziploc® bag, and then inserted into a waterproof Pelican 1085 case. Attempts were made to also store the interface cable inside the Pelican case, but the o-ring seals wouldn't seat properly with both the tablet and the computer inside, so the cable was carried separately in a Ziploc® bag. To address moisture concerns, particularly after the case had been opened during RSP launch, a desiccant cartridge was placed inside the Pelican case to keep the computer as dry as possible, then the whole assembly placed inside a cave pack to minimize dirt penetration and ease transport. To date the tablet computer has always been operated by finger on the screen, but a stylus has always been packed along with the interface cable. This was a hedge against muddy fingers that couldn't be cleaned, and may be necessary to operate the Radon Vision software on the tablet if the operator is lacking finger dexterity (which can occur for a hypothermic caver). Figure 4 shows the tablet computer being used to initialize an RSP in Kemling cave.

Second, once successfully at the sampling site, a procedure had to be developed to install the batteries and initialize the RSP without damaging the monitor. This meant more pressure to select a relatively drip-free and mud-free sampling location, but also a much greater demand for clean hands on the part of the operator. Packaging small towels in Ziploc® bags to clean hands in the cave was helpful. A quarter was always carried along to open the battery chamber, typically stored in the bottom of the carrying case for the RSP. For removal of the RSP at the end of the sampling period, the tablet was not required. The switch on the front panel of the RSP was moved from Run to Stop, and the unit transported out of the cave with the batteries installed, as it was assumed that at this point the data was written to memory and any subsequent battery-jostle on the trip out of the cave would not impact the stored data.

To date, five experimental sets with nine RSP trials have been undertaken using the new tablet-launching approach for the RSP, and no errors have been encountered. Of these trials, two have required lengthy and difficult carries to the sampling site. One in Kemling Cave involved a carry of ca. 500 meters, including two body-sized restrictions, several chimney-climbs, and much crawling. Another trial in Coldwater Cave involved over a mile of transport, largely through roomy passage but including two swims. The tablet utilized for this study was an 11-inch model, which was the smallest available with a full USB port via the College's purchasing contracts. By the time it was packaged in the Pelican case, it was somewhat unwieldy – it was nearly impossible for a single person to carry both the RSP and the packaged tablet computer, unless the tablet was carried outside a cave pack and exposed to the cave mud. Although the tablet by itself was a handy size, by the time it was fully packaged it was slightly too large to be carried in anything but a jumbo-sized cave pack for transport. A 10-inch model of the same Venue Pro tablet is now available with a full-sized USB port, and if that unit (or an even smaller one in the future) could be packaged in a smaller case, cave transport would become significantly easier. However, moving to a smaller screen might preclude software operation via finger due to the smaller menu headings, potentially requiring stylus-only operation.

Conclusions

Cave environments provide a challenge for measurements made with continuous radon monitors, given the mud, moisture, and the difficulty of transporting the devices. The RSP proved robust and reliable for in-cave work. Forty two in-cave trials with the RSP were completed without any loss of data. The RS was not as robust, and should not be used in this type of harsh environment. Modified tripod mounts proved useful for suspending the RSP from the handle of its carrying case during data collection; the rotated orientation of the RSP that resulted did not produce data that was different than with the standard orientation of the RSP horizontally on its bottom. Use of Tyvek® envelopes during trials to protect the RSP against the cave environment was essential and its use did not impact either the radon measurement or that of temperature, pressure, or relative humidity. The relative humidity data collected by the RSP was not reliable in the extreme humidity found in the caves unless an equilibration period of more than a week was available. PRHTEMP sensors fared no better providing stable humidity readings in the same environment. Temperature and pressure measurements from the RSP were reliable, but if precise data are required for calculations or correlations with radon levels, it would be preferable to supplement the RSP with a PRHTEMP sensor for better precision regarding these parameters. In exchange for the requirement of carrying more equipment, data collected by the RSP could be safeguarded from errors by transporting the unit to the sampling site without batteries, installing the batteries upon arrival, and initializing the units in situ via a tablet computer. Nine trials were completed using the tablet to launch the RSP in the cave, all free from error.

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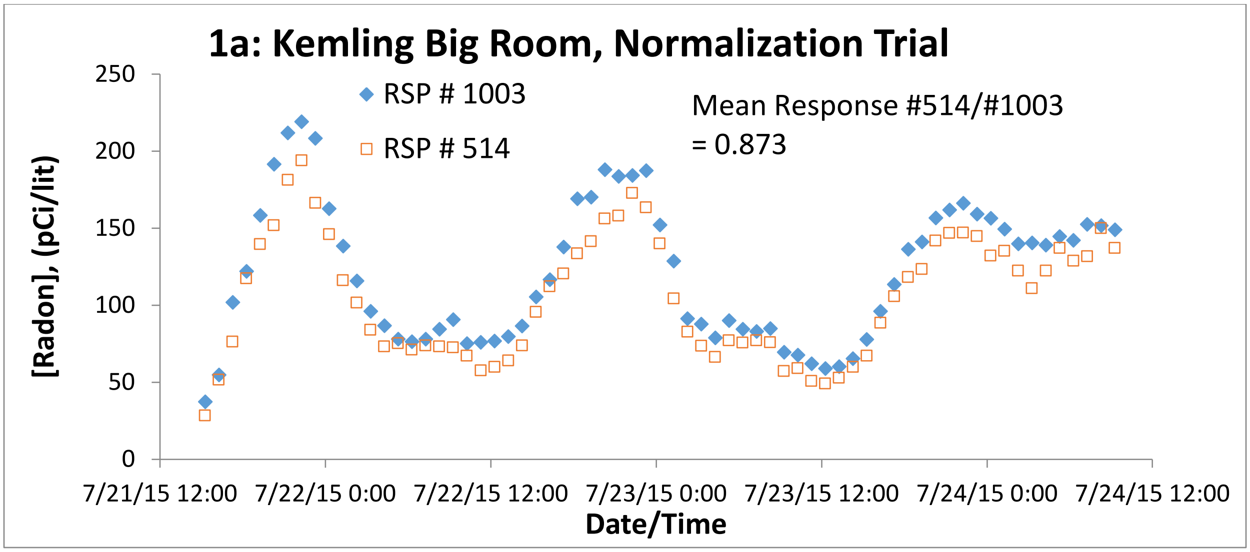
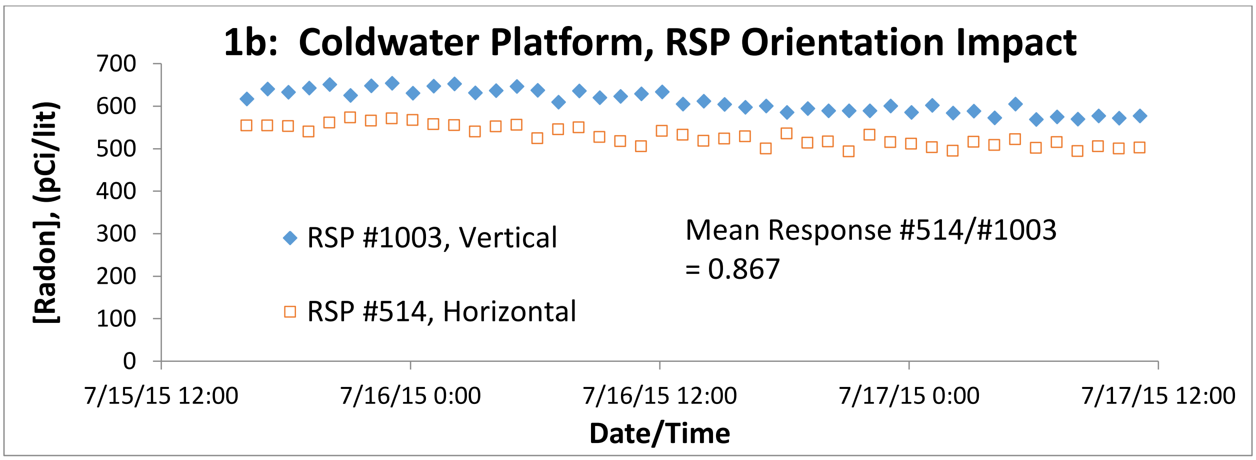
Tables and Figures





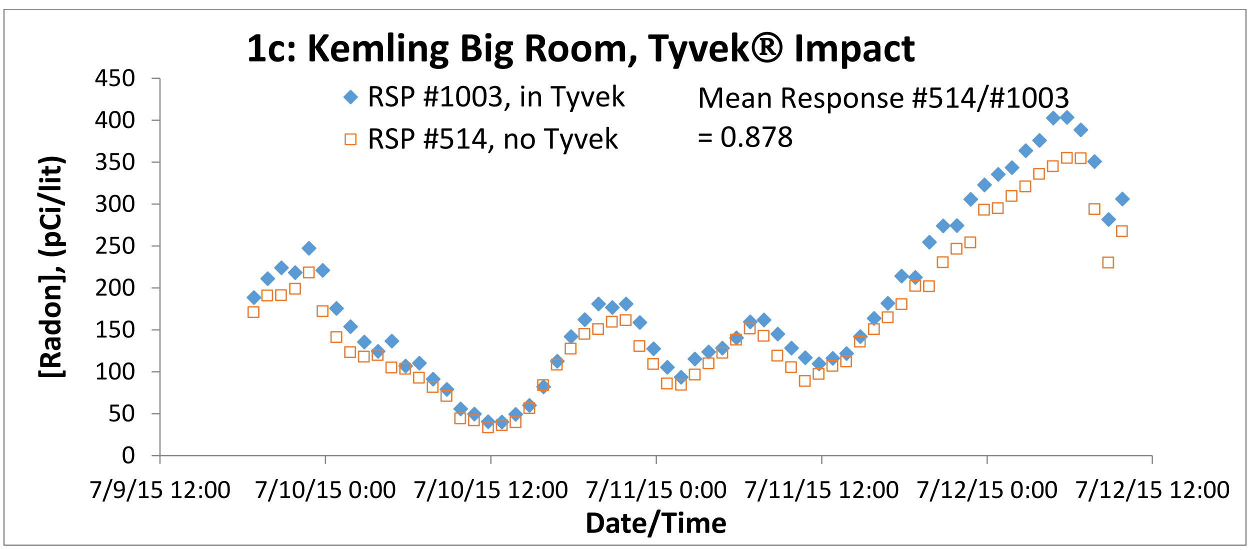


Figure (1): Impact of Tyvek barrier bags and orientation on RSP radon measurements.

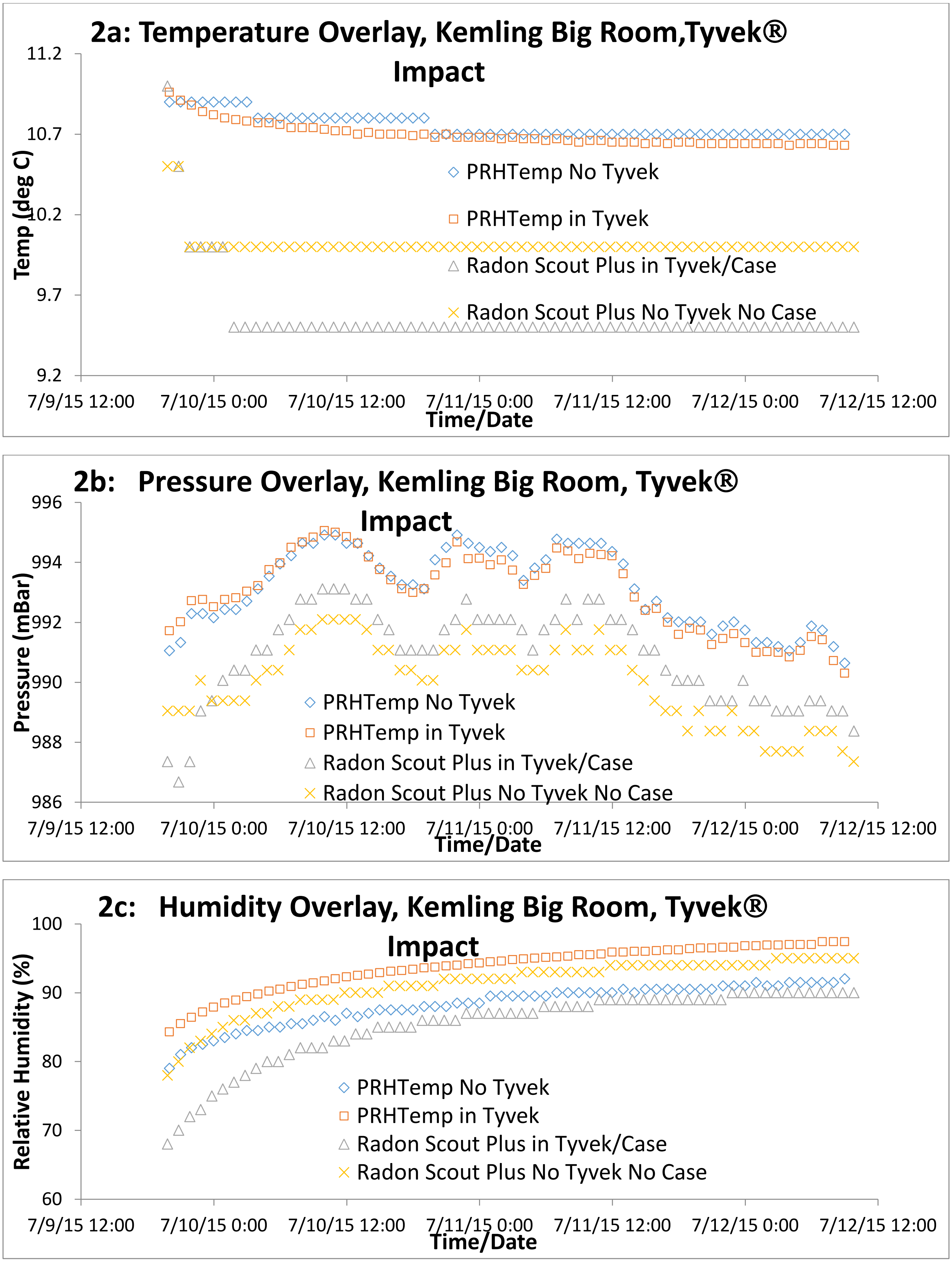


Figure (2): Impact of Tyvek® barrier bags on temperature, pressure, and humidity readings.

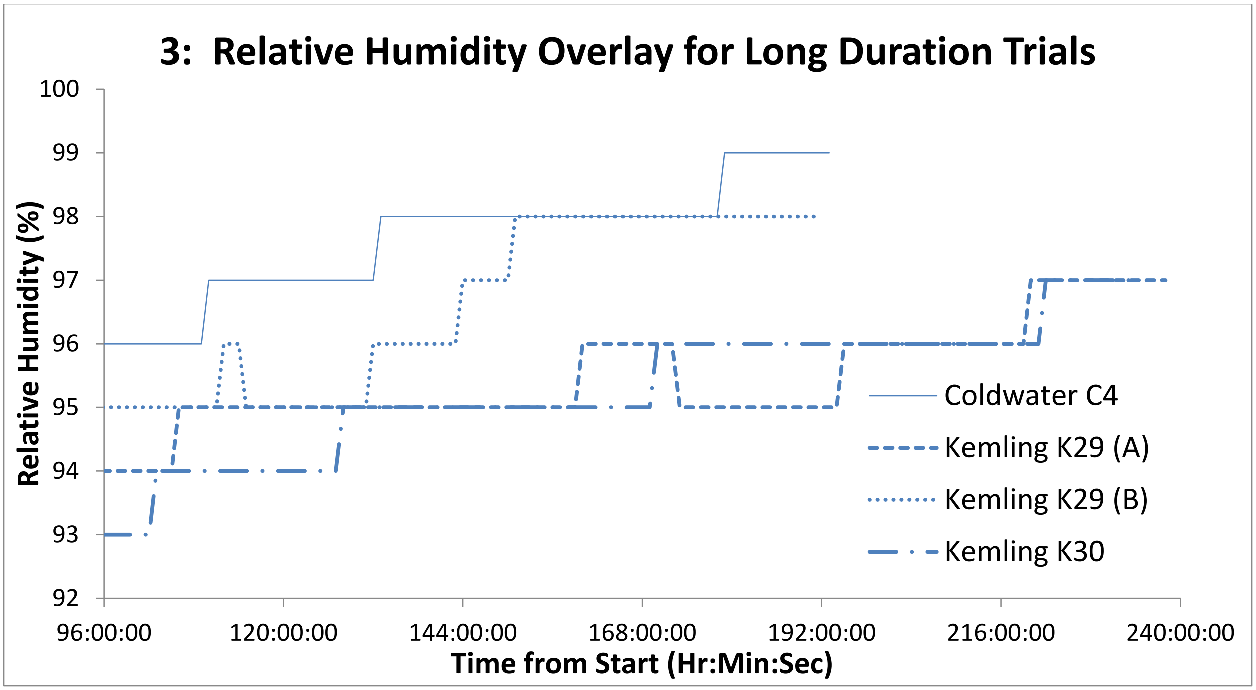


Figure (3): RSP relative humidity measurements for long duration in-cave trials.

Figure (4): Using a tablet computer to launch the RSP in Kemling Cave.

Exp #, Date Range	Unit S/N	Cave	Exp Duration	Perceived Data Fidelity
17, July 20-22 2012	325	Coldwater	25 hr	OK
20, Sept 14-22 2012	325	Kemling	7.5 days	[Radon] went to zero 3 days into the trial
22, November 1-7 2012	325	Coldwater	25 hr	[Radon] went to zero 8 hrs into the trial
25, December 11-14 2012	325	Coldwater	21 hr	[Radon] went to zero 12 hrs into the trial
26, Jan 23 - Feb 2 2013	45	Coldwater	8 days	OK, Loaner unit
28, May 9-12, 2013	329	Coldwater	25 hr	OK, New unit
34, July 14-18 2013	329	Coldwater	28 hr	OK
35, July 25-Aug 1 2013	329	Kemling	2 hr	OK
37, Sept 10-16, 2013	329	Kemling	4 days	[Radon] went to zero 3 days into the trial
38, Sept 16-20 2013	329	Kemling	4 days	[Radon] went to zero 2 days into the trial
40, Sept 22-26 2013	329	Kemling	4 days	[Radon] went to zero 1.5 days into the trial
41, Sept 29 - Oct 2 2013	329	Kemling	3 days	[Radon] went to zero 2 days into the trial
42, Oct 5-9 2013	329	Kemling	3 days	[Radon] went to zero after a few hours

Table (1): Operation log for in-cave use of the Radon Scout.