DEPTH PROFILING OF RADON IN VERTICAL SHAFTS USING ELECTRET IONIZATION CHAMBERS

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Abstract

The variability and uncertainty of underground radon migration makes it difficult to predict which homes will accumulate significant radon concentrations, and which ones will not. As part of a long-term effort to better understand underground movement of this gas, cave environments have been adopted as a laboratory for study. Vertical shafts are a common feature of cave morphology, and the ability to produce a depth profile of radon activity in these shafts is of interest. This paper provides a detailed presentation of the development of sampling methodology to permit mapping of radon activity as a function of shaft height using E-PERM® sensors, and then reviews subsequent efforts to improve the quality of the experimental data obtained.

Introduction

A research program in progress at Knox College has been measuring cave radon activity and correlating it to environmental factors inside and outside the caves. Whereas cave radon measurements are an interesting subject for study, from a broader perspective caves serve as model systems that allow probing the mysterious realm of underground radon movement, which is a vital link in the chain of events from the formation of radon to its accumulation in indoor spaces. The group has explored both the use of continuous radon monitors (CRM, Welch, 2015) and electret ionization chambers (EIC, Welch, 2016) as sensors for in-cave measurements. Cave radon activity has proven to be a complex entity, as the activity varies over time and with location within the caves. The temporal variation time scale has been demonstrated in some cave locations to be quite short (Welch, 2016), and as a result whenever comparisons of radon activity at different cave locations are desired, the sensors for the differing locations being compared need to be run concurrently to negate any time variations.

Most of the in-cave work to date has placed the sensors on elevated ledges and mud/sand banks naturally present in the passage to minimize the risk of sensor exposure to water. In some cases, tripods and other artificial implements have been used to create a dry sampling location in spots that otherwise lacked one. This has worked successfully, but for a large multi-sensor study, it becomes logistically difficult to transport both the sensors and their tripods for each station. One significant feature of cave morphology is that cave formation is not strictly two-dimensional in nature, but often involves vertical offsets that are typically referred to as pits, domes, or shafts, depending on whether they are encountered by the caver at the top (pits, shafts) or the bottom (domes, shafts). These features involve dissolution of the bedrock by aggressive groundwater that is following a line of weakness in the rock (Palmer, 2007). The resulting features range in size from a body length to 603 meters height/depth (Gulden, 2017), and often embody gateways that represent transitions between very different regions of a cave and very different types of passages.

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It is desirable to be able to probe a vertical shaft for radon activity, because collecting data points only at the top and the bottom of such a shaft provides insufficient detail to fully understand the radon movement in these spaces. Most cave shafts lack ledges and floors at intermediate heights, so development of techniques to measure radon in “mid-air” were needed. For method development, the entry shaft of Kemling Cave was selected as a model system (Figure (1)).

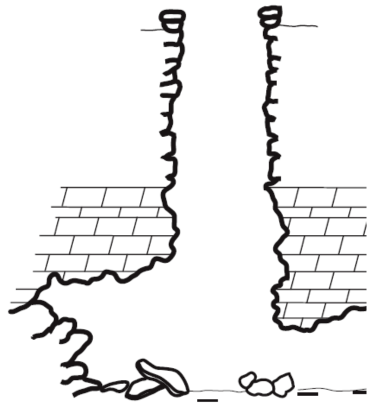

Figure (1): Profile view of the Kemling Cave entry shaft, looking north. Height 7.19 meters. Sketch by Ed Klausner.

This cave lies near Dubuque, IA, and has 3.51 kilometers of surveyed passages (Klausner, 2017). The entrance pit drops vertically 7.19 meters to a floor, where horizontal passage opens as a crawlway that leads toward the rest of the cave. Given the location of the cave, and that the pit is at the cave entrance, it provided easy access for implementation of experiments, and the presence of an extension ladder within the pit eliminated the necessity of time-consuming ropework while performing the study. Once an apparatus was developed that functioned well in the Kemling entrance pit, the aim was to show that the apparatus could subsequently be adapted for pits deeper in the cave. Although indoor use was in general outside the realm of the ongoing study, one might imagine that someone might have an interest in producing a depth profile within a building while probing the oft-cited “stack effect” (Cothern, 1987).

Given that the study had a goal of utilizing the depth-profiling apparatus for things beyond the model system, the equipment first and foremost had to be flexible in capability. Underground vertical shafts vary in depth, so the ability to customize the height of the apparatus was crucial. If the depth-profiling apparatus was to be used in cave locations remote from the entrance, it had to be composed of parts capable of being broken down into compact components that could be transported through stoops, crawls, and climbs, preferably in backpacks. Anything to be used in the cave had to be fairly robust, as it would be exposed to mud, water, and high airborne particulate burden, while being bumped and contused during transport. Given that the apparatus would feature multiple sensors running concurrently, the sensors had to be relatively inexpensive to stay within budget constraints. Past experience has shown that the measured radon activities seen in Kemling Cave span from 0 to greater than 1000 pCi/L. As such, the sensors for the depth-profiling apparatus needed to be flexible enough to allow low uncertainty measurements regardless of radon levels and experimental duration.

EIC units appeared to be a good fit for the sensor portion of the depth-profiling apparatus. CRM units can adapt to the cave environment (Welch, 2015), but the need for multiple sensors and the high cost of CRMs prevented their use. Depending on the configuration, the EIC units cost $50-$150 each. EIC units had proven robust enough for in-cave applications (Welch, 2016) and were compact enough for multiples to be transported by a single caver. EIC sensitivity was a function of the choice of chamber and electret. The sensitivity was proportional to chamber volume, so the 210-ml S chambers were 3.6 times as sensitive as the 58-ml L-OO chambers (Kotrappa, 1981). ST electrets were designed for short-term experiments, and therefore were more sensitive by 13 times than the LT electrets, which were designed for long-term experiments (George, 2011). By informed choice of the chamber and the electret, one could properly customize a set of EIC sensors for the radon activity present and the experiment duration being planned. However, knowledge of the radon activity in advance was guesswork at best, and it was therefore nice to have some flexibility in choice of experimental duration to compensate. Proper selection of the EIC yielded results with low uncertainty (Welch, 2016), which was needed when comparing multiple sensors within a single experiment. The superstructure of the apparatus that was to hold the EIC sensors needed to address the list of desires as well, in particular needing to be inexpensive, easily transported, and flexible enough to allow implementation in pits of differing depths and to allow different depth intervals for data collection.

Materials

E-PERM® EIC sensors consisted of an electret of either the short-term [ST] or long-term [LT] variety, and a chamber of either the H, S, or L-OO variety, all from Rad Elec Inc. Electret voltages were measured with a SPER-1E electret voltage reader (Rad Elec Inc.). Calculations were done with the WinSper software Version 2.3.21 (Rad Elec Inc.) or with Radon Report Manager software Version 3.8.44 (Rad Elec Inc.). Background gamma radiation exposure was evaluated with the Model 2 Gamma Ray Dosimeter manipulated with the Model 909B charger from Arrow-Tech. Temporal measurements of radon activity were measured using Radon Scout Plus continuous radon monitors and Radon Vision software Version 6.0.7 (Rad Elec Inc.).

The depth-profiling apparatus will hereafter be referred to as a “radon tower”. The integral components of the tower are depicted in Figure (2). It became clear early on that to be able to span any kind of vertical interval, the radon tower needed to be suspended from anchor points on the top of the tower that could support the tower weight, plus those of any attached sensors. A 1.3-cm (½-inch) diameter aluminum rod was suspended across the pit as a crossbar. Obviously, very wide pits were ruled out with this type of anchor. If spanning the top of the pit was not workable, it would be possible to drill bolts in the wall and construct an anchor for the crossbar. The aluminum crossbar was inserted through a 1.3-cm (½-inch) ID PVC tee and then clamps were used to keep the tee from moving laterally. Schedule 80 PVC threaded risers (or nipples) could then be threaded into the tee, and with the application of couplers, additional risers could be added to the radon tower to customize its height. Risers of 45.7 cm (18 in) length proved to be optimum, as they were the longest pieces that easily fit into a standard caving backpack; 30.5 cm (12 in) and 61.0 cm (24 in) pieces were used on occasion as well. Hollow PVC pieces were relatively light, and they also proved easy to clean when soiled with cave mud. Flexibility in the sampling depth interval was gained by drilling holes at multiple levels in each PVC riser, and by the ability to insert “spacer” risers that had no mounted sensors in between the “sample” risers that did have sensors. Eyebolts were threaded through the holes in the PVC risers, and then kept

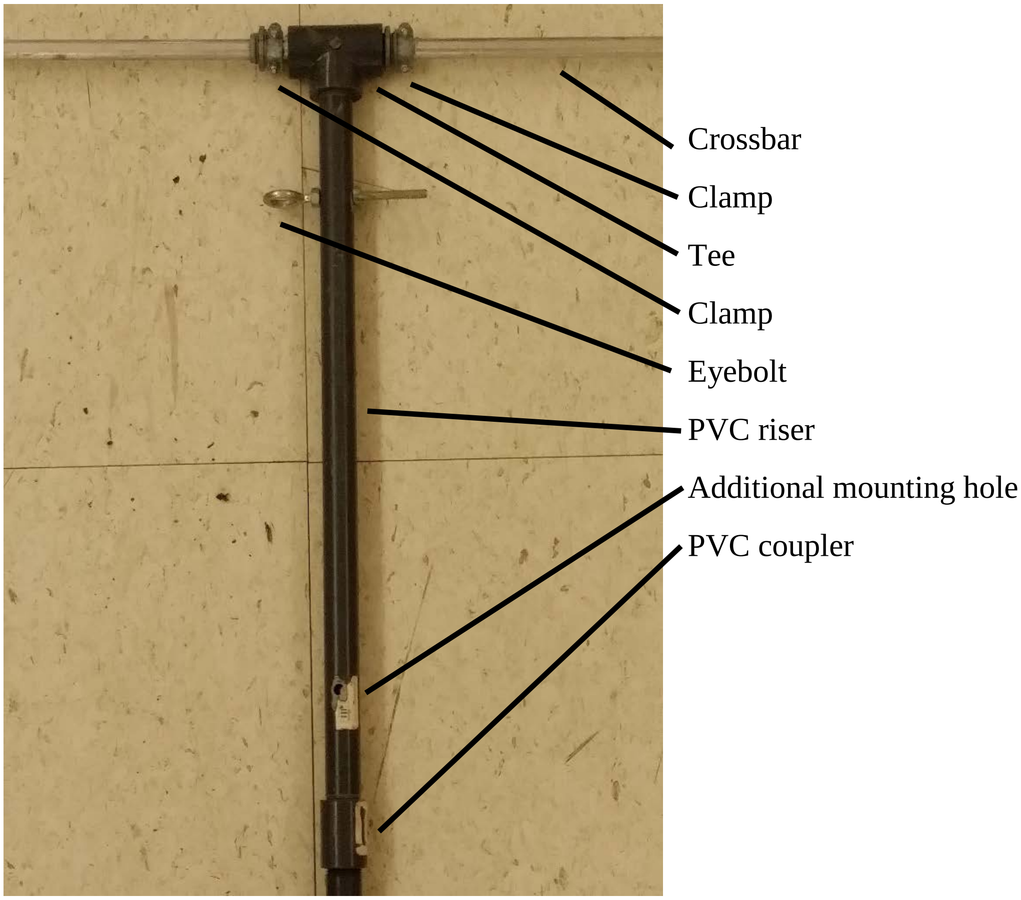

Figure (2): Segments of the radon tower.

in place with wing nuts. Mini-carabiners (7.6 cm length) were threaded through the eye of the eyebolts. These could suspend an L-OO chamber from the hole in the on-off slider (see Figure (3A)). The S chambers had a mounting loop on the top; a 2.5-cm keyring was threaded through the loop, and then the combination could be suspended from the mini-carabiners hanging from the eyebolts (Figure (3B)). Although the L-OO chambers could be suspended from their slider, it should be noted that this required the sensor be detached from the mounting whenever it was switched between on and off, and that this, coupled with the need to detach the clip or pin that kept the slider in place, led to an awkward and time-consuming switching process. When in the dark, cold, muddy cave environment, while climbing to reach a sensor partway up the radon tower, this was not ideal. Switching the S chamber electrets between on and off while they were suspended from the radon tower was simple and straightforward.

Results and Discussion

Experimental Phase I

For the Kemling Cave entrance pit model system, a 2-meter crossbar was ideal, as it easily suspended the radon tower from the stone walls lining the pit. The tower configuration chosen for the model system was to use thirteen of the 45.7-cm PVC risers, each holding a single eyebolt, with a single 61.0-cm piece at the bottom sporting two eyebolts top and bottom. An additional sensor was typically placed on the floor of the pit just below the lowest riser, yielding

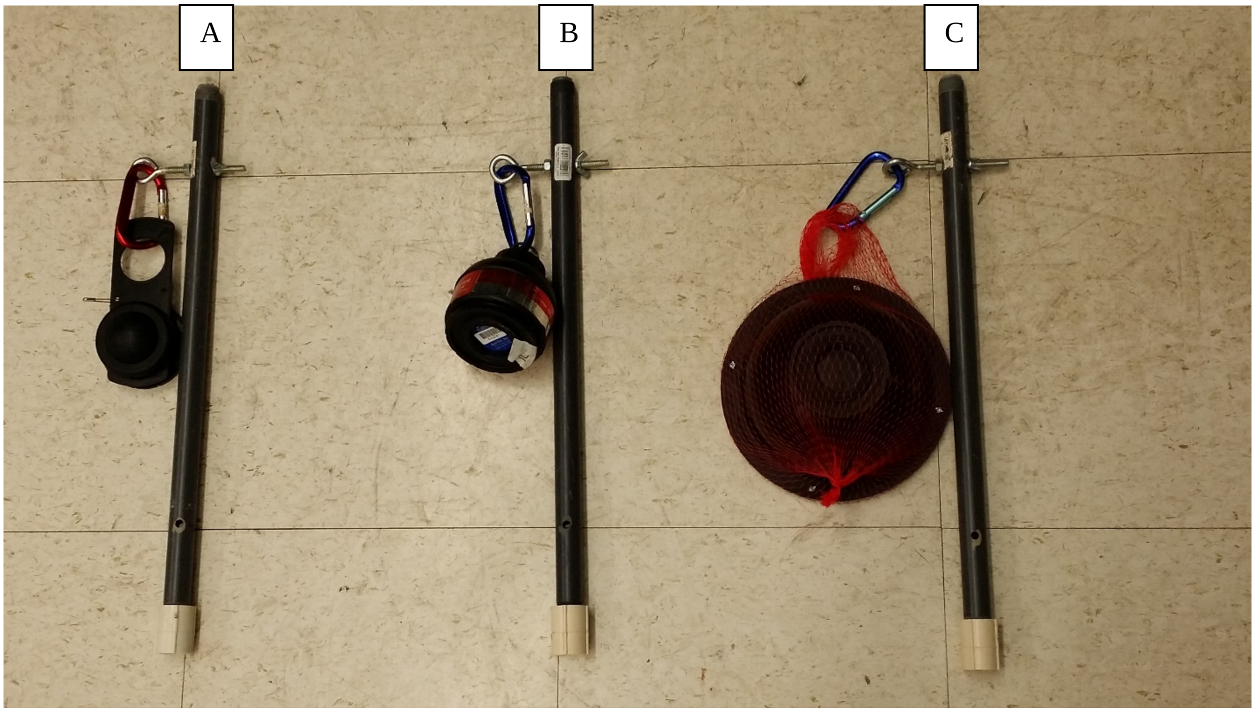

Figure (3): Suspending the E-PERM® sensors from the radon tower. A) L-OO chamber, B) S chamber, C) H chamber.

a set of sixteen measurements spread throughout the height of the shaft. As noted above, the E-PERM® sensors were configured with S chambers to take advantage of their hook for hanging on the tower, and their easily-operated on/off switch. The radon tower structure was constructed first, followed by hanging of the E-PERM® sensors on the corresponding eyebolt while all were in their off position. Once the sensors were all hung, they were turned on (opened) and the times recorded as quickly as possible to minimize the difference in time duration values within the sensor set. When ending the experiment, the sensors were all turned off (closed) and times recorded in as short a time span as possible. Then the experimental apparatus was dismantled. The "before" and "after" voltages on the electrets were interrogated in the climate-controlled laboratory after at least eight hours of residence time. This permitted the electrets to completely equilibrate to the laboratory temperature, which was done to avoid the deleterious impact of having a temperature difference for the two readings (Welch, 2016).

Trial IA, the initial radon tower experiment in the model system, was undertaken in September 2012. Only one sensor was placed on the bottom PVC riser for this trial, in contrast to subsequent trials. Numerous radon readings had been taken at the bottom of the Kemling entry shaft prior to this experiment, and they had typically yielded over 100 pCi/L. Expecting this type of activity for the experiment, the less-sensitive LT electrets were chosen for this trial, coupled with a 24- hour experiment duration. The depth profile found is shown in Figure (4). Despite the expectation of high radon, almost all of the sensors showed minimal activity. The cave presumably was in a phase where it was inhaling air from the surface. As such, the entry shaft was flushed with surface air containing almost no radon, and extremely low activities were found. Compounding the problem, given the selection of the less-sensitive LT electrets, the very small voltage changes that resulted from the low radon activities produced very large relative uncertainties for the measurement (Welch, 2016) – for many of the depths the absolute uncertainty was higher than the radon activity itself. Finally, there appeared to be a couple of outliers in the set (not obvious in Figure (4), but obvious when the Trial IA is plotted by itself and autoscaled), which had no plausible explanation given the site and the experiment other than poor measurement. Overall, the data derived from the trial was a disappointment. However, the radon tower did work as planned, and the finding that minimal radon inhabited the Kemling entry shaft was of some value, but nothing of interest could be derived from comparing activities at different depths.

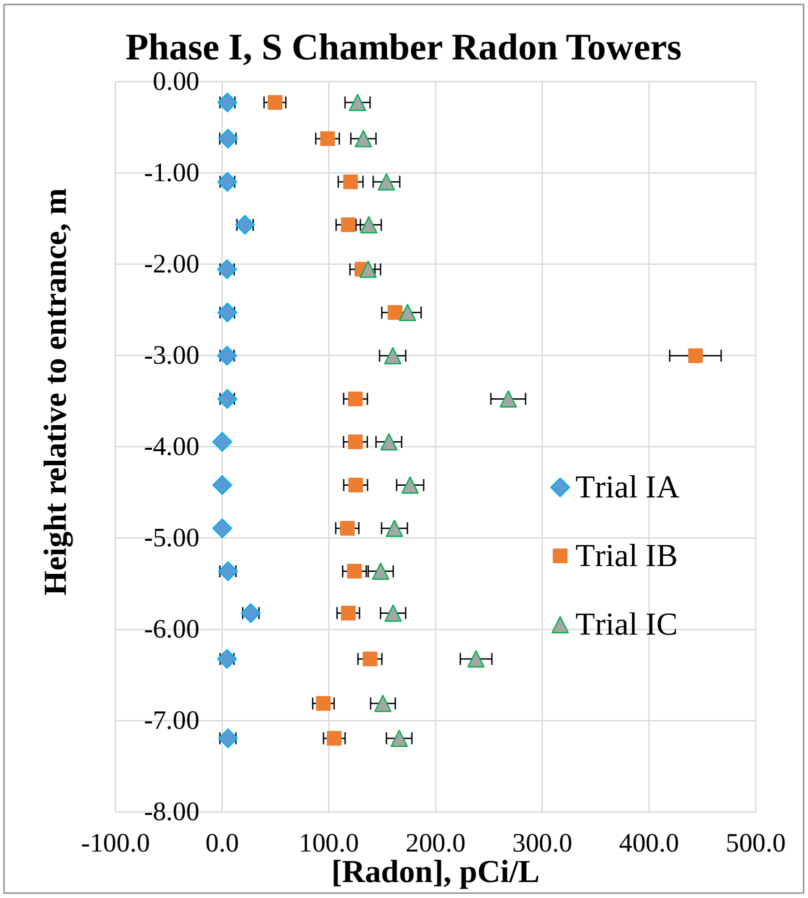

Figure (4): Phase I, S chamber radon towers

Improvement was sought in two subsequent 24-hour trials, IB and IC, which were run back-to-back on consecutive days. For these, a preliminary radon activity measurement was made within the shaft, and the high value measured informed the decision to deploy LT electrets with S chambers, as in Trial IA. Trial IC immediately followed Trial IB, with the only difference being that the top of the shaft was covered with a plastic tarpaulin to block air exchange. Although a hermetic seal could not be expected, the tarpaulin cover was designed to minimize the impact of inhaling/exhaling cave airflow and the high variability associated with transitions between these states. The tarpaulin also blocked cave entry or exit of the bats that were living within the cave, but given the time of year (November-December), the bats were in hibernation and did not need to leave the cave during the experiment. Outcomes for Trials IB and IC are also shown on Figure (4). Although the absolute uncertainties were much larger than those seen in the initial trial, the relative uncertainties were considerably smaller (IA=122.0%, IB=9.7%, IC=7.7%). The radon activities were higher in Trial IC with the sealed shaft than in IB, in otherwise duplicate conditions. This could be due to minimizing the inhalation of low-radon surface air, which seemed a certain contributor to the difference seen at -0.23 m, but given the high radon variability seen in prior studies in this location (Welch, 2016), it was impossible to clearly conclude that the difference was due to the shaft-sealing as opposed to just a normal variation. Outliers were again present in both trials, with a particularly bad one seen in Trial IB at -3.00 meters.

One particularly interesting finding can be derived from the data in Figure (4). Trial IB had a rather unusual feature whereby two of the lowest radon activities within the set were observed for the bottom two points (-6.81 m and -7.19 m) collected in the shaft, whereas the next point upward (-6.32 m) jumped to a considerably higher activity, in fact one of the highest values found in the trial. For Trial IC, the -6.32 m data point was also large -- so high as to suggest that it was an outlier. The two points below were again much smaller than the -6.32 m value, but they were not low compared to the balance of the data from trial. As can be seen in Figure (1), the ceiling of the passage leading to the bulk of the cave takes off at the bottom of the entry shaft at very close to the -6.32 m level. Cold surface weather was experienced during Trials IB and IC: the average surface temperature for Trial IB was 4.0 ºC, while the average surface temperature for Trial IC was 2.9 ºC (Weather Underground, 2017). Once beyond the entrance area, caves in general feature air temperatures that correlate with the mean year-round temperature on the surface above the cave (Palmer, 2007). This group has measured the temperature deep inside Kemling Cave multiple times, and have found values in the range of 10.3-11.4 ºC. So the surface air temperature was considerably colder than the cave air throughout Trials IB and IC. It has been noted that caves commonly inhale and exhale air through their entrances. For a single-entrance cave, these processes cannot proceed uninterrupted for extended periods, as they would produce a pressure rise or drop in the cave, which would tend to counteract the airflow pattern. However, concurrent bidirectional airflow can occur via a single cave entrance – i.e. simultaneous inhaling and exhaling (Senger, 1977). This type of flow has the advantage that it would not cause a pressure change within a single-entrance cave if the flow volumes in each direction were similar. Bidirectional flow is borne out from the bottom three points in Trial IB. As the cave inhaled, the cold, dense surface air dropped to the bottom of the shaft. Compared to the less-dense cave air, the inhaled surface air stayed along the floor when entering the bulk of the cave, leading to lowered radon activity at this depth strata. The cave air was enriched in radon, and when exhaled to balance the inhalation flow, its low density had it being exhaled along the roof of the passage, where it encountered the -6.32 m sensor, resulting in the elevated reading. When the top of the shaft was covered with a tarpaulin in Trial IC, the sensors along the shaft floor did not read such a low radon activity; there was still colder air in the entry shaft, but inhalation of outside, radon-poor air was limited. The -6.32 m radon activity was still much higher though, suggesting that bidirectional airflow still existed despite the tarpaulin over the entrance – it presumably just cycled around inside the cave rather than involving the outside air.

Revamping the Experimental Approach

The Phase I trials confirmed that the practice of using the radon tower was working in general, but there was a sense that the data that it yielded had not been optimized. In particular, the trials contained outliers in the data set, and there was the general perception that the precision of the collected data was not yet to the point that the radon activities at different depths could be compared to one another with confidence. A plan was made to revise the approach to the radon tower experiment with an eye toward improving precision and reducing outliers, using the same model system as before. Looking ahead, once better performance could be achieved for the model system, the plan was to test the system in a more remote location inside Kemling Cave, and to also demonstrate that the radon tower could be deployed for indoor use.

Three strategies to potentially improve performance were identified as things to test on the model system with a radon tower in Phase II. First of all, the phenomenon of the cave inhaling and exhaling was known to exacerbate the rapid variation in radon activity observed near the entrance to the cave. The Trial IC approach of placing a tarpaulin over the cave entry did show evidence of limiting exchange of cave air with surface air, but it also suggested that the entry shaft was still impacted by air currents coming from within the cave. By adding a second tarpaulin at the bottom of the Kemling entry shaft, it was hoped that a more isolated model system could be produced, less influenced by the vagaries of the cave winds. This was done for all Phase II model system trials. Secondly, the known high temporal variability of radon activity in this location (Welch, 2016) seemed problematic for producing precise measurements. Prior work found it unlikely that the radon activity near the Kemling entrance shaft would remain anywhere close to constant during a 24-hour experimental duration. If the time window for sampling were decreased, could this lead to more uniform radon activity during the experiment, permitting greater output precision? This could be tested by adapting a more sensitive E-PERM® sensor configuration. Finally, the issue of outliers within the data set was to be tackled by collecting replicate measurements at each depth, producing a data set rather than a single reading. Given the high variability in radon activity, the replicate measurements had to be made concurrently for this approach to work.

Experimental Phase II

Making the E-PERM® sensors more sensitive could easily be accomplished by switching from the LT electrets used in Phase I to the ST electrets, which were 13 times more sensitive. Inquiries with the vendor determined that no other, more sensitive electrets were being sold. However, selection of the EIC chamber also impacted sensitivity, with signal rising in proportion to the volume of the chamber. S chambers had been used in Phase I, and no larger chambers were in house. A chat with the vendor revealed that they sold a larger chamber called the H chamber (Kotrappa, 2009), and we were loaned some demonstration models to evaluate them. The H chambers had a volume of 960 ml, making them 4.6 times more sensitive than the S chambers. This was an advantage in seeking a shorter time window for a radon tower experiment, but it would be a limitation in terms of the transportability of the tower when needing to carry multiple sensors. Given the size and the number of H chambers available, the strategy of taking replicate readings at each depth could not be pursued. The H chambers also had no on/off switch nor any kind of hook that could be used to connect them to the radon tower. The vendor suggested (Stieff, 2017) that the H chambers could be mounted on the radon tower by using plastic mesh bags of the sort used in the fruit department of a supermarket, which were adapted for use successfully (see Figure (3C)). Given that the Kemling entry shaft was easily accessible, this meant: A) the size of the H chambers would be manageable for tests, and B) the lack of an on/off switch, while still a concern, could have its impact minimized. The ST electrets were always installed on the surface above the cave, such that the chamber was initially filled with outside air. Although the sensors were technically in the on position once the electret was in place, the few minutes in the radon-poor surface air were gauged to have only a small impact on the output. The clock was started on the experiment at the point each E-PERM® was taken into the cave, and installation of the electrets on the tower was done as rapidly as possible. At the termination of the experiment, all of the sensors were taken to the surface quickly. Since the chambers were presumably full of radon-rich cave air, the electrets were still accumulating signal even after they were removed from the cave. The end time for the trial was recorded when the electret was removed from the chamber and capped, and this operation was also done with haste.

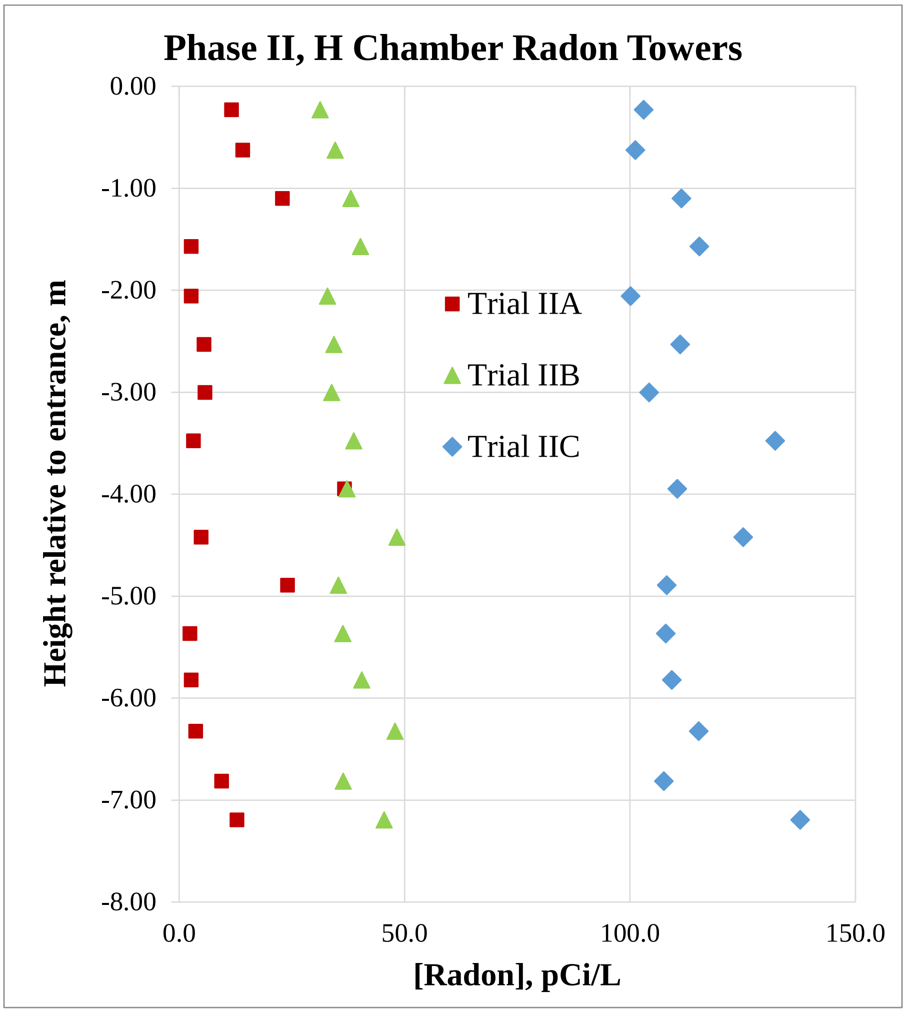

Figure (5): Phase II, H chamber radon towers.

Three trials, IIA through IIC, were run with the H chambers on the model system, with outcomes shown in Figure (5). Trial IIA was an 8-hour trial using H chambers and ST electrets. The tarpaulins were installed immediately before commencement of the trial. Due to the time frame of the experiment being during daylight hours, there was no concern of preventing bats from exiting the cave. Due to time pressure, a preliminary measurement of radon in the system was not made, and unfortunately the sealed shaft held very low-radon air for the trial, which limited the precision of the output since the voltage change was small. Subsequent trials IIB and IIC were informed by preliminary measurements, and both yielded better output. Trial IIB was an 8-hour trial that spanned the daylight hours. Unfortunately, despite the shorter time window, the radon level still varied considerably during that time (see Figure (6)). Trial IIC was a short trial of circa 2 hours in duration, timed to run when the radon was at a high level, allowing the short experiment to provide sufficient change in voltage to minimize uncertainty. Both IIB and IIC did not have any obvious outliers, and the precision was considered good but not great. The lack of an on/off switch was perceived as a real limitation. There was always a degree of uncertainty knowing an appropriate value for the start and stop times, and even if the start times were measured well, the extreme sensitivity of the sensor coupled with the time needed to undertake the start and stop operations lacking an on/off switch caused problems. The sensors were being stopped when radon activity was much higher than when they were started (see Figure (6)), so a few extra minutes spent in the high-radon conditions at the end of the trial could greatly bias the overall integrated average. Although the H chamber radon towers appear to be a serviceable approach, to really pursue high precision data it was felt that the development of an on/off switch was needed. This will be the subject of future work, prior to more attempts to deploy H chamber radon towers.

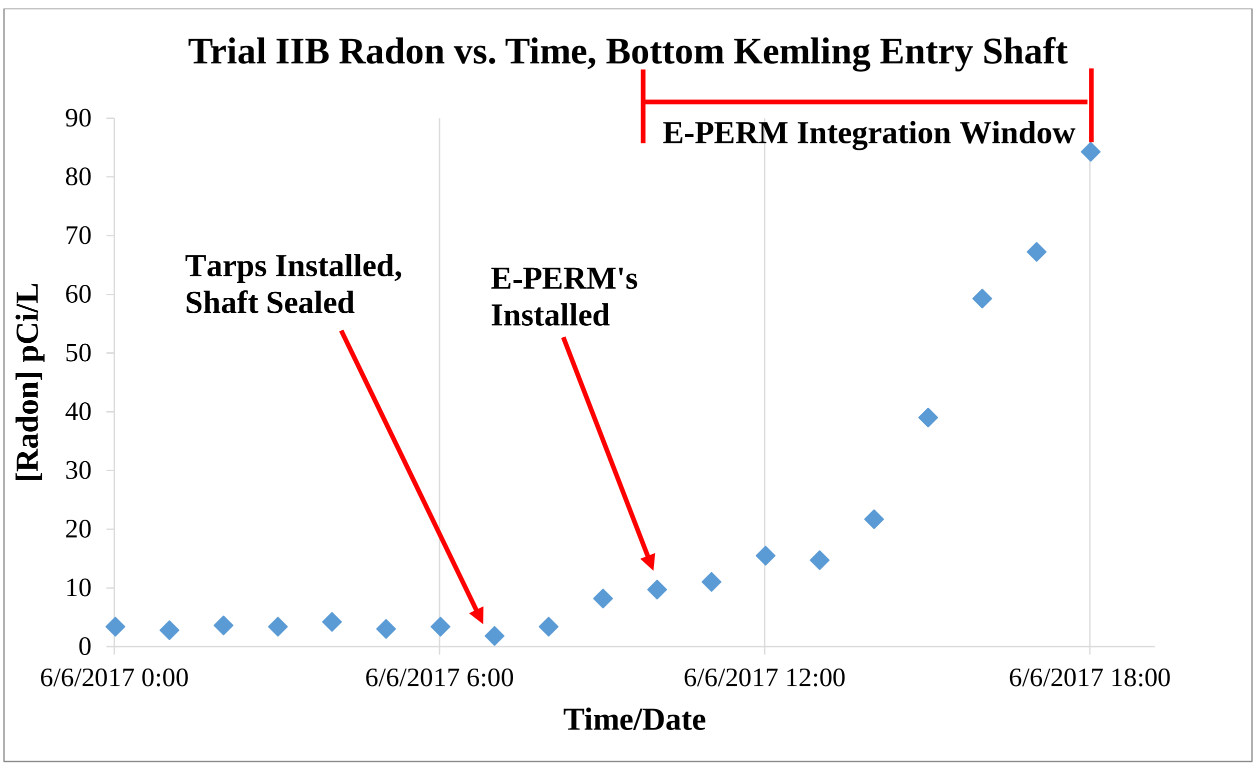

Figure (6): Radon change over time during Trial IIB.

This left testing of the replicate-measurement strategy as a means to pursue greater output precision. Trial IID was designed to place duplicate sensors at each depth on the radon tower. H chambers were clearly unsatisfactory for this approach given insufficient supply, their large size, and the lack of an on/off switch -- a problem that would be exacerbated by a trial featuring twice as many sensors to manipulate. So S chambers and ST electrets were the order of the day. The mini-carabiner mounting of the S chambers adapted well to duplicates, as both could be suspended from the same eyebolt at the same time. Given the configuration and prior data, a 24 hour duration was selected for trial IID. Since this time frame would be problematic for the bats residing in the cave, the tarpaulin coverings at shaft top and bottom were modified to allow installation of a 30.5 cm (12 in) diameter flexible duct pipe from top to bottom, permitting the bats to exit and enter the cave while still providing a sealed system inside the shaft for the radon measurements. Ultrasound sensors confirmed that the bats were successfully using the duct pipe prior to its utilization in this trial.

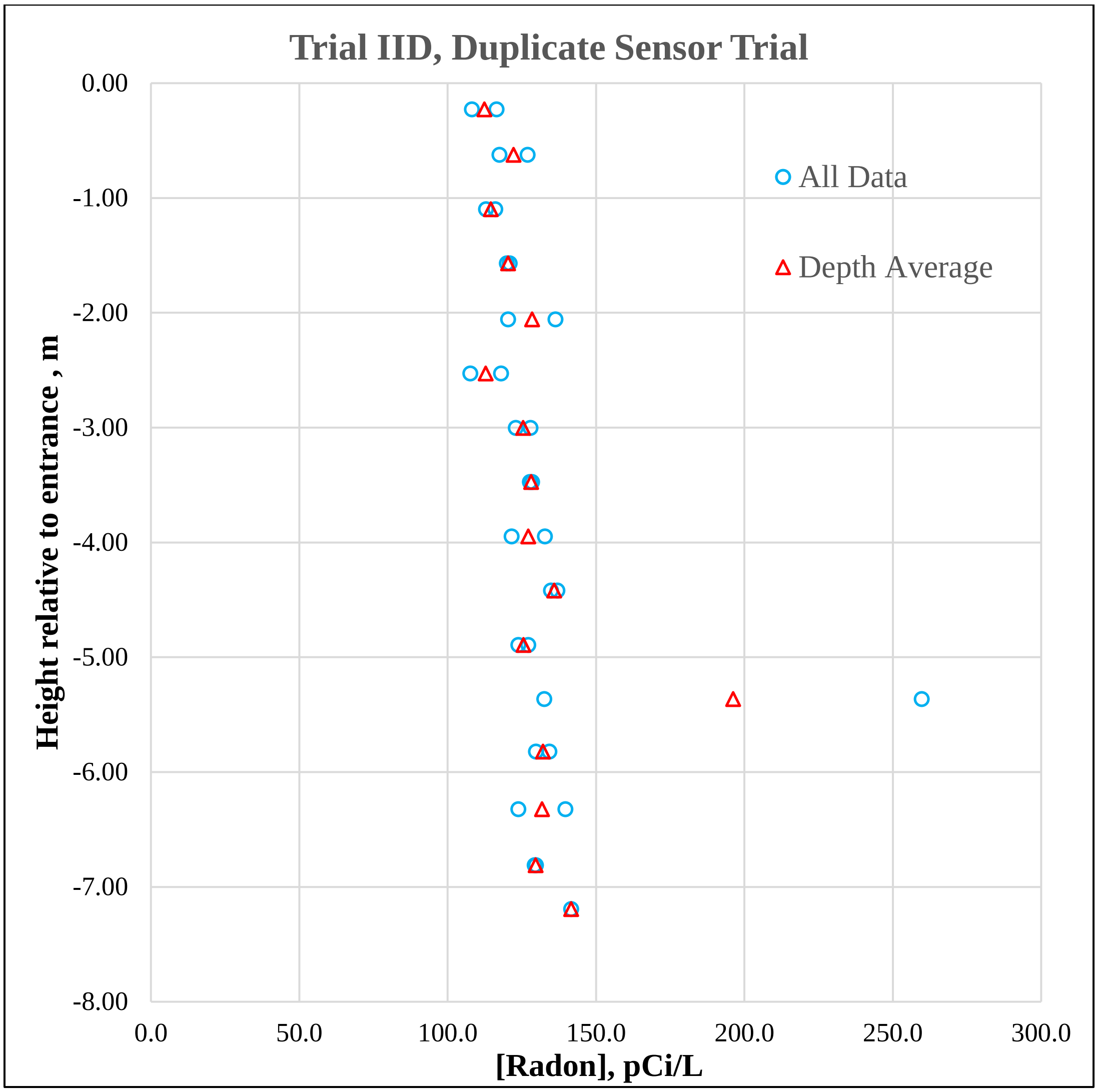

Figure (7): Trial IID data, duplicate sensor trial.

A preliminary measurement of radon activity was made just prior to Trial IID, but while good in the short term, it underestimated the activity during the bulk of the trial, and as such large electret voltage changes were ultimately registered. Although this ensured low relative uncertainties for the measurements, it also consumed a larger portion of the electret capacity than intended. This made for an expensive experiment, and led to some of the electret voltages being depleted to below 200 V, where the response became non-linear (Welch, 2016). However, a logarithmic fitting algorithm has recently been developed (Kotrappa, 2013), which allows good fit for electret voltages down to 100V. This algorithm was not available with the WinSper software which had been in use, so a switch was made to the Radon Report Manager software for this and subsequent trials, which did utilize the logarithmic fit. Figure (7) shows both the raw radon activities and the averages for each depth on the tower using the duplicate sensor approach. Only a single sensor was deployed at the lowest depth due to an experimental oversight. The average produced what looked to be improved precision, but it was marred by an outlier at -5.36 m. The raw data for this height show that one of the two sensors generated a value fairly consistent with the rest of the set, but the other sensor measured an excessively high

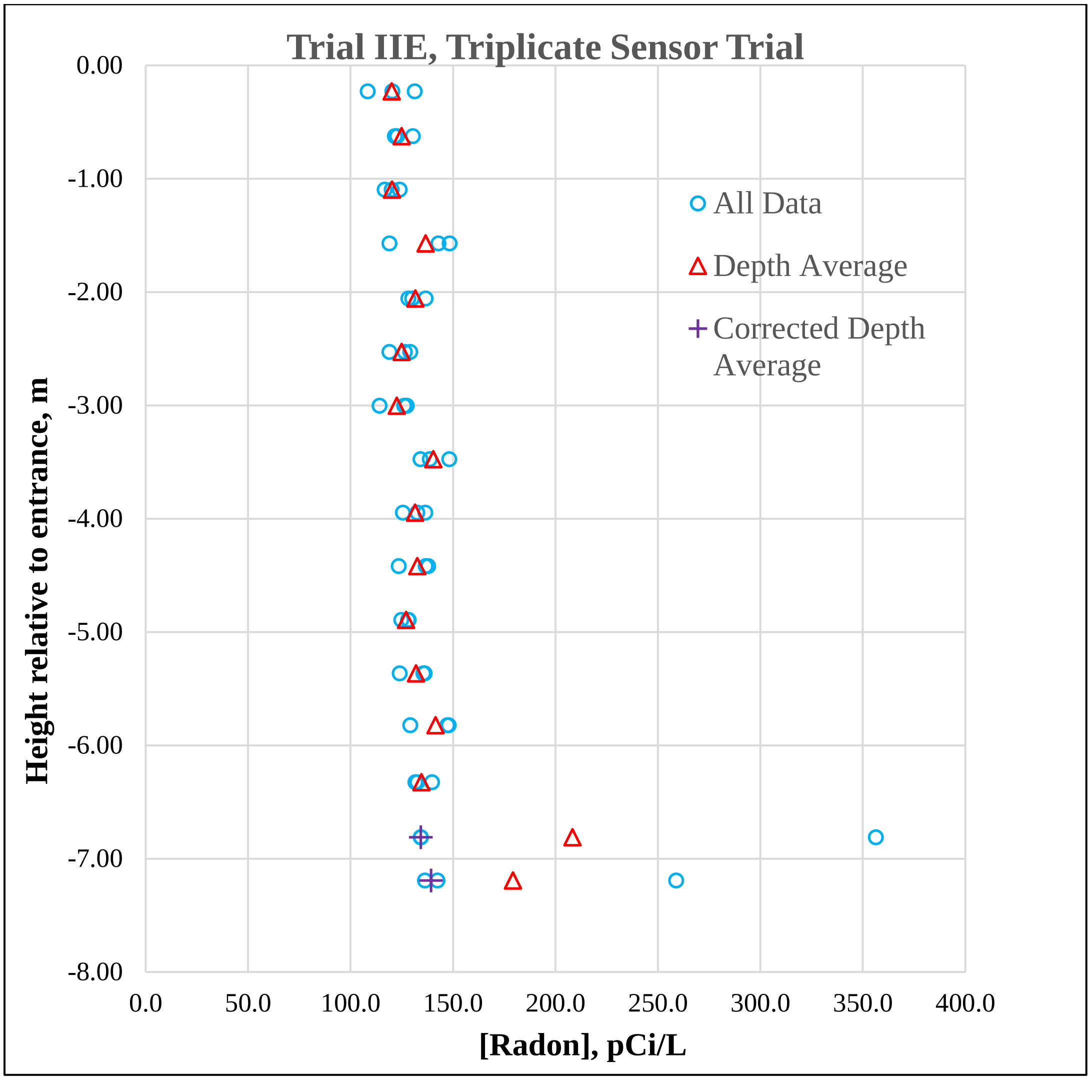

Figure (8): Trial IIE, triplicate sensor trial.

value. However, there was no noteworthy problem with the sensor that could explain its excessively high value, meaning that other than arbitrary caprice, there was no way to throw out this point and use the remaining value to represent this depth.

With the experience of the duplicate sensor trial IID and the outlier in mind, a further modification was sought by moving to triplicate data points at each height. While fitting the "more is better" mantra when measuring a central tendency of a statistical set, the biggest factor supporting this move was that with a data set of three values it became possible to run standard statistical tests to reject an outlying data point. Trial IIE was a triplicate sensor trial, run with S chambers and ST electrets as a 6-hour experiment to reduce the voltage changes and the expense. This also meant that installation of the duct pipe "bat tunnel" was not needed due to the daytime execution of the experiment. Figure (8) shows both the raw data and the depth average for trial IIE. It is evident that both of the lowest tower heights have a single outlier in the set, and that even when the three trials were averaged that the outliers still biased the value for that height. Two standard statistical tests common in analytical chemistry were applied to the sets containing the apparent outliers, the Q-test (Dean, 1951) at the standard 90% confidence level (Fritz, 1987), and the Grubbs Test (Grubbs, 1969) at the standard 95% confidence level (Harris, 2016). Both approaches concluded that both outliers could be rejected at these confidence levels. After removal of these data points, the resulting corrected averages for the two lowest depths were added as purple "+" icons in Figure (8). With the corrected averages, Trial IIE produced what looked to be the best performance seen for a radon tower. Although the theoretical depth profile has not been completely developed, it was clear that the theoretical change in radon activity with depth, for the scale of these experiments, will be small. As a result, it was felt that a rough estimate of trial precision could be made by calculating the relative standard deviation of the entire data set from each tower. Table (1) summarizes the relative standard deviations for all of the trials run on the model system with the entry shaft sealed; this information confirms the superiority of the triplicate S-chamber approach.

Table (1): Relative standard deviations for all trials on the model system with a sealed entry shaft.

Trial	Chamber	Electret	Multiplicity	Comment	RSD%
IIA	H	ST	1		96.0
IIB	H	ST	1		13.5
IIC	H	ST	1		9.52
IID	S	ST	2	all data	19.7
IID	S	ST	2	average	14.9
IIE	S	ST	3	all data	27.7
IIE	S	ST	3	average	16.9
IIE	S	ST	3	after stat tests	5.30

Feeling comfortable with the performance of the triplicate S-chamber tower, this same approach was then adapted to both an indoor trial and a trial much deeper in Kemling Cave. Obviously, not every building is laid out to allow such a radon tower to be installed, but the presence of a stairwell allowed deployment of such an experiment in the chemistry wing of the Science and Math Center at Knox College (see Figure (9)). The crossbar was placed on a landing between floors and thirteen 45.7-cm PVC riser segments suspended down the stairwell. Access to hang/switch E-PERM® sensors in the middle of the tower was enabled by a stepladder. ST electrets were utilized for a 38-hour experiment, with the outcome shown in Figure (10). No significant outliers were observed, so the Figure (10) averages are derived from all data points for the trial. Since the indoor locale for the test was a highly ventilated chemistry wing, the radon levels were low as would be expected. Thus, the radon tower appeared clearly feasible for indoor use.

Finally, a triplicate S-chamber radon tower was broken into components, then transported and constructed at a location circa 250 meters inside Kemling Cave, near the “Leap of Faith” over the Grand Canyon Passage. To reach this spot, some walking, some stooping, some crawling, and some chimneying (climbing off the floor wedged between the side walls) were all required. The PVC risers of the tower fit into a single caving backpack, the E-PERM® sensors fit into two

Figure (9): Indoor radon tower.

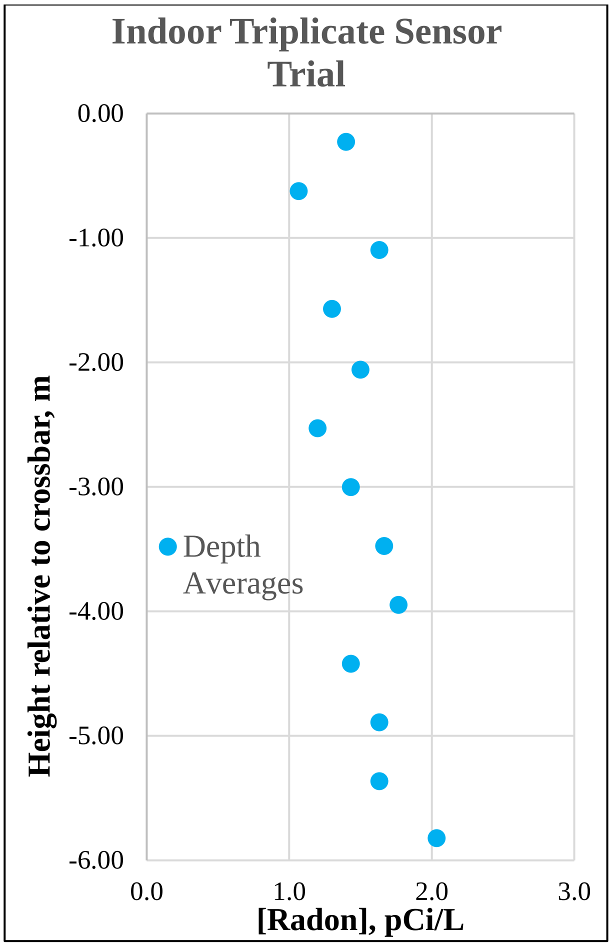

Figure (10): Indoor triplicate sensor trial.

5-gallon buckets (hard sides for better shock resistance compared to a backpack), and the crossbar was carried separately (see Figure (11)). The crossbar was wedged between limestone pockets at the top of the canyon, and a tower with ten 45.7-cm PVC risers constructed, extending close to the floor of the passage at this point (Figure (12)). Access to most of the sensors was via chimneying the walls – typically one person did the chimneying to the level needed, and the other person lowered sensors in clusters of three to their counterpart. The cave was open for this 2.5-hour trial (i.e. no tarpaulins) using ST electrets. Figure (13) shows the depth averages for this experiment, with no points being statistically rejected. The results were intriguing, with the obvious inflection point at -1.57 meters. The -1.57 meter sensor set is the one directly below the lowest one that can be seen in Figure (12); it would hang roughly at foot-level for the person shown in the figure. The location of the radon tower was at the junction of a North-South passage and an East-West passage, with North being to the left in Figure (12). The floor of the East-West passage coincides approximately with the maxima of the radon activity, whereas the North-South Passage extends down to the base of the radon tower. There are clearly some interesting airflow patterns in this complex passage area.

Figure (11): Kemling Cave internal radon Tower components ready for transport.

Figure (12): Kemling Cave internal radon tower construction.

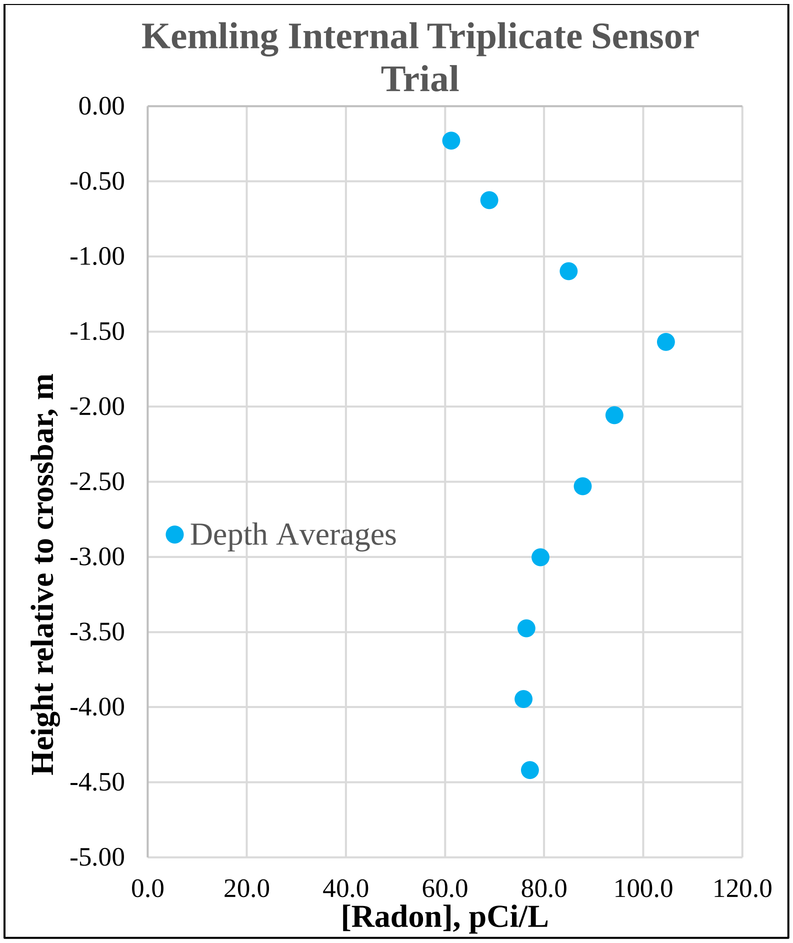

Figure (13): Deep cave triplicate sensor trial.

Conclusions

A radon tower is a viable approach to producing a depth profile of radon activity in a cave shaft, allowing experimentalists to map radon levels and the air patterns that impact them. The tower needs to be suspended from above, and a mechanism needed to access the different heights of the tower. This is done most easily by wedging a crossbar across of the top of the shaft and hanging the apparatus from that, but it would be possible to drill a bolt anchor if the crossbar approach was out of the question. Access to the sensors on the tower is most easily done with ladder or climbing, but could be accomplished by rappelling/ascending a rope suspended down the shaft, as this approach is a common caving technique. By applying very sensitive EIC sensors, one can shrink the time frame of the experiment. This is helpful as it increases the chances of avoiding the normal radon activity fluctuations seen in caves, and it also increases the chances that the experiment can be accomplished in a short time frame. Although H chambers work with a radon tower, it was felt that the development of an on/off switch for the E-PERM® sensors containing these electrets was necessary to achieve high precision work. Radon towers using triplicate S chambers have produced the best data seen to date. Work is in progress to take experimental data from such a tower collected in the Kemling entry shaft model system and to then compare that with a theoretical function predicting the change in radon activity as a function of depth.

Triplicate sensor trials will require more expense for consumable (electret) and non-consumable (chamber) items, and they also require carrying of greater loads to deploy such a tower deep in a cave. Nevertheless, a trial was set up 250 meters inside Kemling Cave and a data set collected by a 2-person team in a single day.

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