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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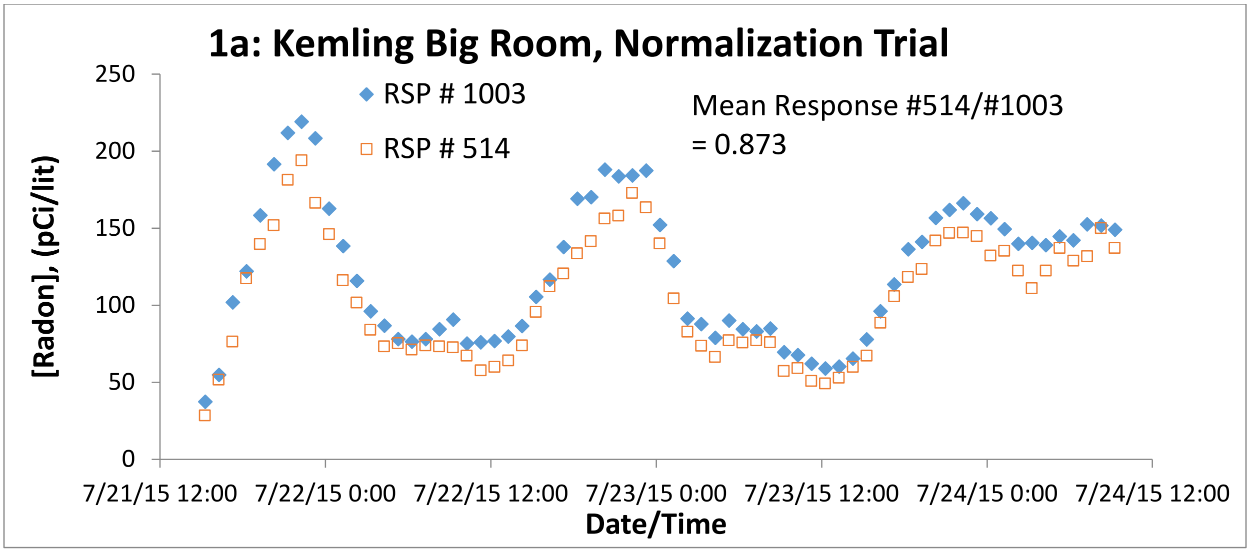
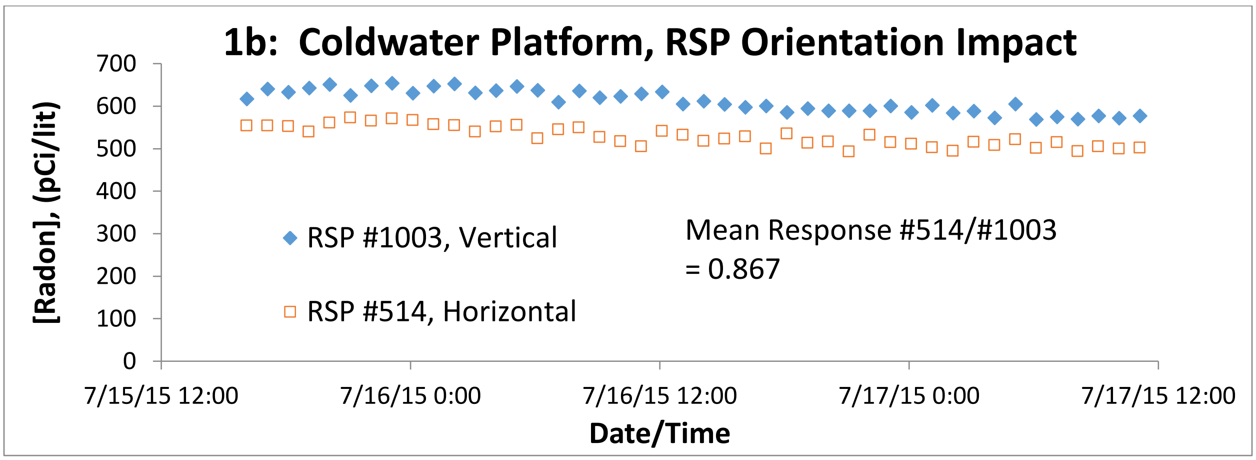
Tables and Figures





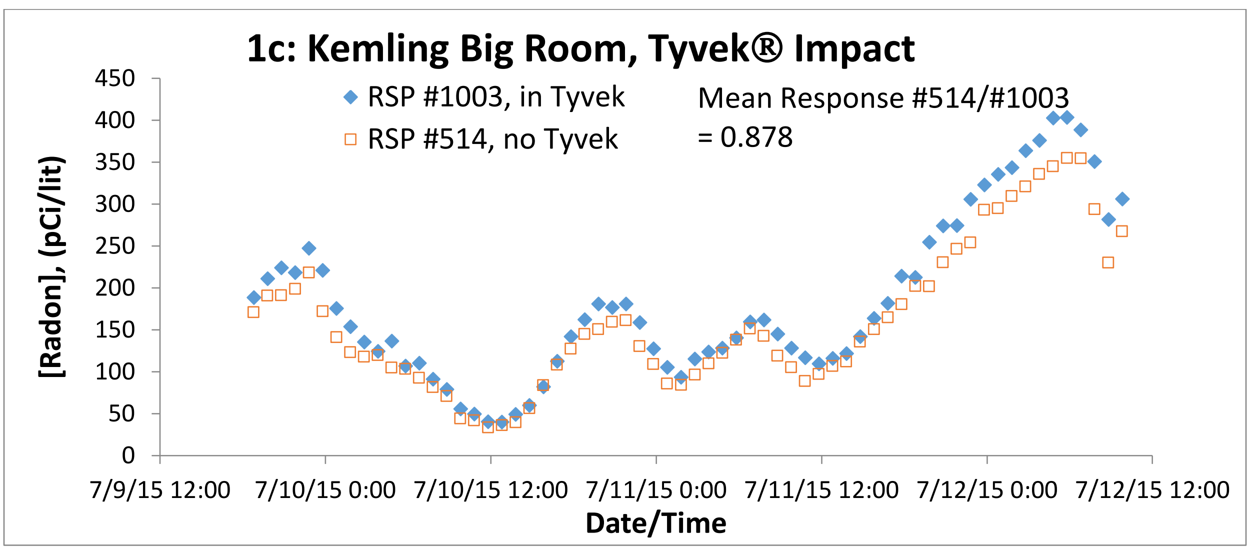


Figure (1): Impact of Tyvek barrier bags and orientation on RSP radon measurements.

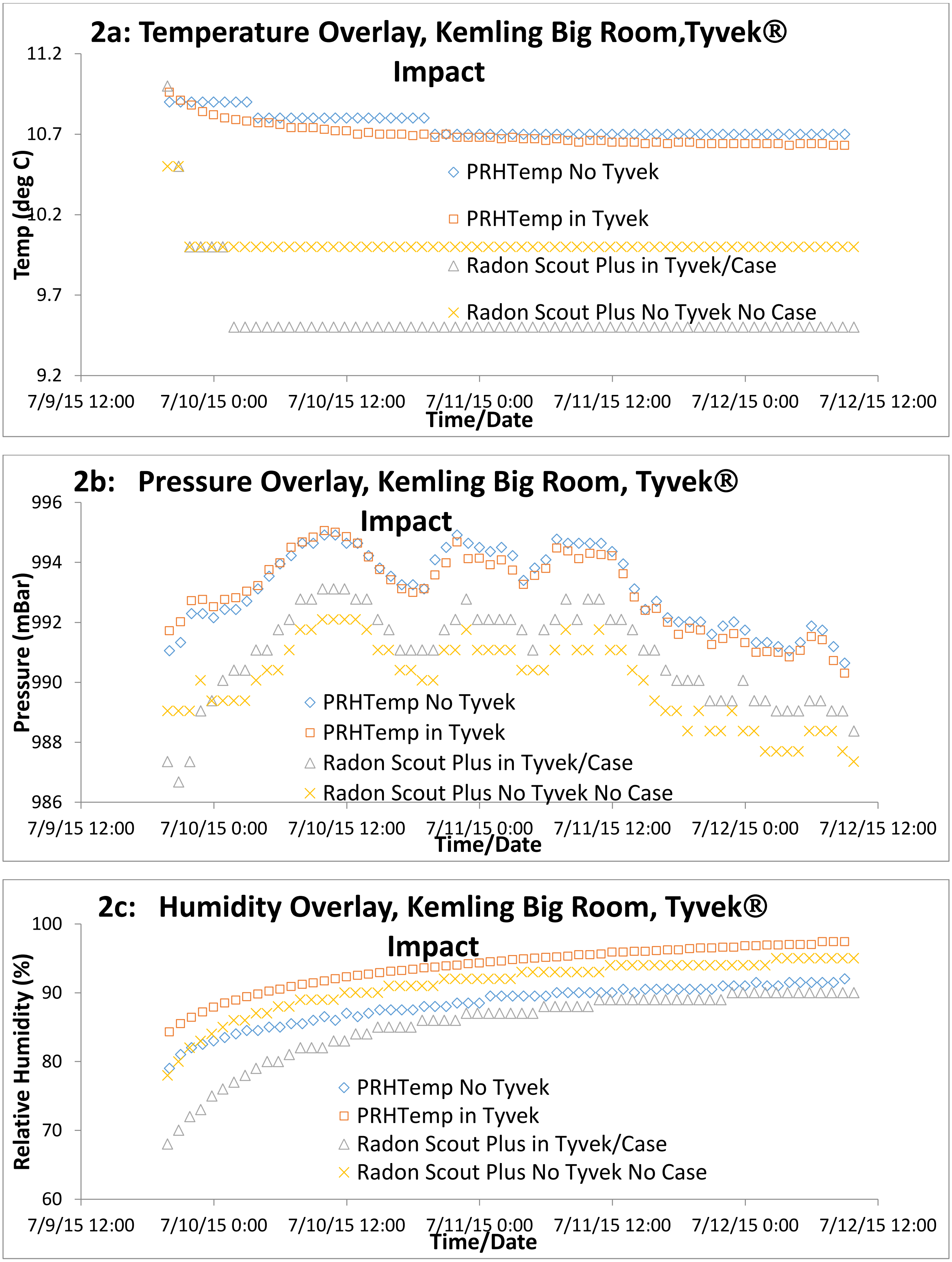


Figure (2): Impact of Tyvek® barrier bags on temperature, pressure, and humidity readings.

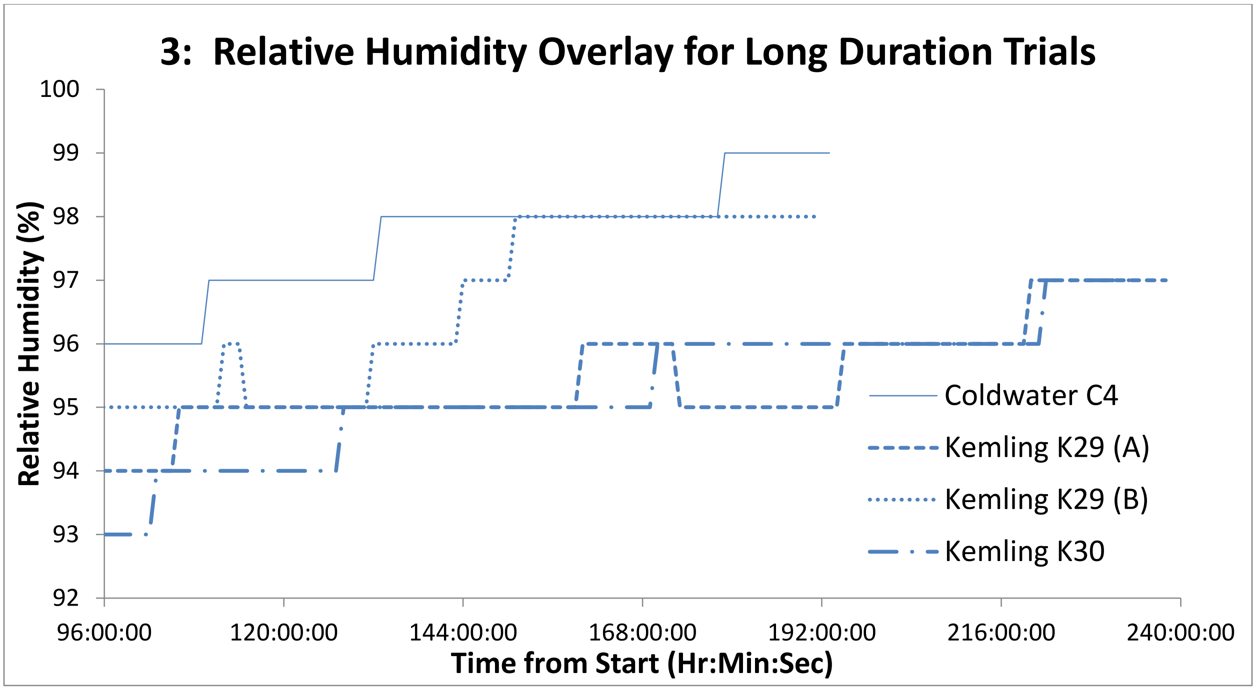


Figure (3): RSP relative humidity measurements for long duration in-cave trials.

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.