USE OF ELECTRET IONIZATION CHAMBERS TO MEASURE RADON IN CAVES

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Abstract

The caves in Northeastern Iowa are the location for a number of radon studies currently in progress, yet they have proven to be challenging sampling environments due to their wetness, mud, high particulate atmosphere, and the difficulty of transporting equipment to the sampling sites. E-PERM® electret ionization chambers were evaluated in this setting for radon measurement. Major concerns included shorting of the electret charge due to physical shock during transport and from particulate or water infiltration. Selection of chamber size and electret sensitivity to permit appropriate precision during the available time window was also a concern. This presentation will detail why E-PERM® units were selected for use, how the units performed in the cave environment, and what special transport and deployment techniques were adapted to ensure the quality of the experimental data.

Introduction

A research program in progress at Knox College is measuring cave radon activity and correlating it to environmental factors. A prior manuscript (Welch, 2015) reviewed the literature regarding radon in caves, and challenges faced when working in this environment. Whereas that work focused on the use of continuous radon monitors (CRM), this effort will explore the utility of electret ionization chambers (EIC) for working in these same caves. An electret is a thin layer of material that will become polarized in an electrical field, yet has sufficient dielectric capability for it to remain stabilized with separated charges for an extended period of time after removal from the field. When the positive surface on an electret is presented toward the inside of a grounded chamber, it is expected to collect electrons from ionization reactions within the chamber, which will incrementally drain the positive voltage on the electret. Since nuclear radiation can produce ionization within a chamber, the EIC thus was suggested as a potential dosimeter (Marvin, 1955). The efficacy of the EIC units in this capacity was greatly increased by the subsequent incorporation of polytetrafluoroethylene (PTFE, Teflon), with its superb dielectric properties, for construction of the electret active surface (Bauser, 1978).

Kotrappa et al. (1981) detailed how to construct a functional electret ionization chamber using a Teflon membrane that could be used to measure radon. This design was refined and eventually was released commercially as the E-PERM® system (Kotrappa, 1988; Kotrappa, 1990). In addition to detailing the system hardware, these prior manuscripts also described proper calibration of the sensor, inherent errors and their calculation, and the dynamic range over which linear response of the sensor could be expected. The E-PERM® sensors showed accurate response in a subsequent field test (Fjeld, 1994) and have since been used for a wide variety of dosimetry applications. Although E-PERM® application for use in measuring radon in cave environments has been limited, they have been shown in non-cave measurements to give

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a response that was not impacted by the temperature and humidity of the sampling site (Kotrappa, 1990), and have shown that they can be successfully deployed in high-radon locales (Kotrappa, 1994). In his review article about radon in caves, Cigna (2005) reported that electret ionization chambers were affected by humidity and required polyethylene encapsulation to function. Nemangwele (2005) utilized electret ionization chambers to look at radon in the Cango Caves of South Africa, and found that when they were deployed alongside continuous radon monitors similar output values resulted. Bruzzone (2006) reported difficulties with EIC sensors in the Toirano's Caves of Italy, postulating that the high CO_2 level in these caves along with the condensation due to excessive humidity was the root cause.

Materials

E-PERM® sensors consisted of an electret of either the short-term [ST] or long-term [LT] variety, and a chamber of either the S or L-OO variety, all from Rad Elec. Electret voltages were measured with a SPER-1E electret voltage reader (Rad Elec). Calculations were done with the WinSper software Version 2.3.21 (Rad Elec). 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 achieved with Radon Scout Plus continuous radon monitors and Radon Vision software Version 6.0.7 (Rad Elec). 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.

Discussion

In contrast to the temporal stream of data points produced by a continuous radon monitor, the EIC sensors produce a single integrated average radon activity measurement per trial. Obviously, a data timeline is more useful than a single point, but it comes at a cost. The Radon Scout Plus CRM used in a prior study (Welch, 2015) currently retails for $2195, whereas all of the E-PERM® EIC configurations in use here cost either $43 or $75 apiece, depending on the chamber selected. As an aside, it should be noted that the electret was a consumable, so the cost of long-term E-PERM® use was effectively higher than their new price tag. The E-PERM® units were also smaller, which was a major advantage for cave travel, which required human-powered transport of sensors in backpacks that were also partly filled with essential survival gear. An S chamber has a volume of 210 ml, the L-OO chamber is 58 ml, whereas a Radon Scout Plus CRM fills 1330 ml. When information was to be gathered at multiple sites within a cave, the larger size and price for the CRM tended to be limiting.

Rather than invest in multiple CRM units, one could do sequential data acquisitions at multiple sites using a single CRM. For surface locales this might be logistically simple, but for cave locations remote from an entrance, each placement or collection of an EIC would require a trip into the cave and a much greater expenditure of time and energy than placing and collecting multiple sensors in a single trip. It should also be considered that if radon activities for multiple cave locations were to be compared to one another, which was typically desired, then measuring at the different sites in a sequential manner with a single CRM would only prove useful if the radon activity was stable over time. This may be a reasonable assumption in a small minority of caves over short time spans, but for most caves this was not a workable assumption due to interactions of the cave atmosphere with the surface atmosphere along with surface climate factors (Cigna, 2005). In numerous cases for caves in the study area, the radon activity can be classified as hypervariable in nature (see Figure (1)), and multi-site comparisons

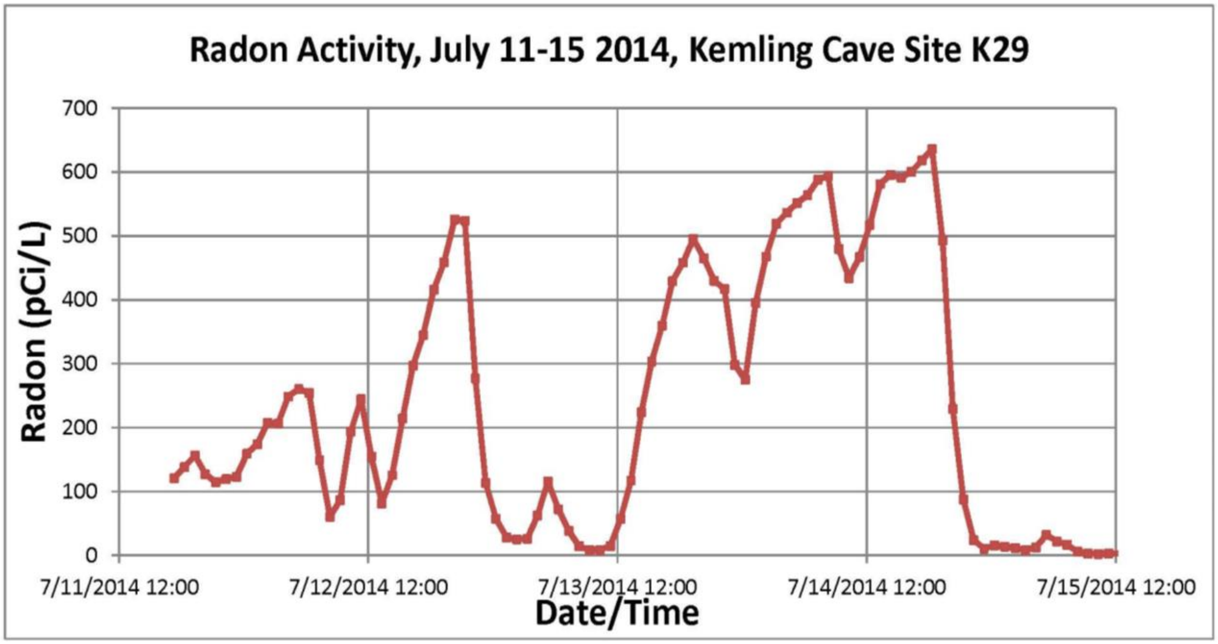

Figure (1): Hypervariable radon activity in a northeast Iowa cave.

absolutely require simultaneous data acquisition. Thus, the properties of the E-PERM® sensors lend themselves to this environment: an experimentalist can afford to buy multiple E-PERM® units, plus has backpack space to carry the multiple units at once and deploy them in the same time frame to normalize for any variability in radon activity. Another factor favoring E-PERM® use in the cave environments was that they do not require a power source for operation, avoiding the need for circuits and batteries that can be sensitive to moisture, mud, and shock during transport. What's more, the only moving parts on the E-PERM® units are the on-off controls. Other than routine cleaning, no repair or maintenance on any of these units has yet been required in nearly five years of use.

Initial concerns at the outset of E-PERM® application mainly involved avoiding short-circuiting the active electret surfaces. The documentation provided with the units (CERTI, 2006 and Rad-Elec, 2015) counsels of protecting the surface from water or particulate deposition, either of which could partially or completely quench the isolated positive voltage on the electrets, and potentially produce the problems reported by Bruzzone (2006). Although the cave environment was typically rich in both water and particulates, the E-PERM® units were operated within Tyvek® envelopes (Stieff, 2012; Welch, 2015), which served a protective function. Physical shocks to the units were not a concern during operation of the sensors, but were significant concerns during transport to and from the sampling sites. Most of the sites required wading in waist-deep and greater water levels on floors that were neither visible nor smooth, so falls and jarring of the backpack were possible. When the E-PERM® units were placed in the off position, the active electret surface was kept covered by a shutter extension of the chamber, with only a small gap between the grounded chamber piece and the positively-charged active surface

– a significant physical shock could short the electrets. Despite these concerns, the number of shorted E-PERM® sensors in circa five years of use has been tiny and mostly due to getting the units getting very wet. Thus, cave transport of the units was adapted to minimize the chance of getting them wet. The E-PERM® sensors were kept in the off position during transport, placed in Tyvek® bags for transport as well as measurement, and the Tyvek®-encased sensors placed inside a kayaking dry bag, which was then carried in a standard water-permeable cave pack. The transporting caver was instructed to hold the cave pack up out of the water when swimming or wading deep sections, and asked to avoid dropping or falling on the pack.

Site selection within the cave was obviously directed at selecting spots that were of scientific interest and geographically distinctive in case the sensors were to be picked up by someone other than the experimentalist who launched them. Although the sensors in all cases were placed out of the water, one always had to consider the potential water level rise resulting from a heavy rain or snowmelt event; it was best to place the sensors at least half a meter above the existing water level. When selecting new sites, a brief pre-launch observation time span was used to monitor ceiling drips on the spot, as this has resulted in shorted sensors in the past, despite the Tyvek® outer shell. The E-PERM® units are passive in nature, so care was taken not to select locations that were sheltered from normal airflow, such as up against a wall. Since carrying tripods for the sites wasn't feasible, most of the sample sites were chosen on top of flat rocks or on the top of mud banks so the natural airflow was not compromised.

The E-PERM® sensors can be configured in multiple ways. Both S and L-OO chambers were available, each with a different size (as noted before, 210 ml and 58 ml respectively). Each will respond to ionization resulting from radon alpha decays within the air volume of the chamber, so the larger the chamber, the greater the sensitivity of the sensor given the same airborne radon concentration. The sensitivity difference should be proportional to the volume ratio of the chambers, so an E-PERM® with an S chamber was expected to be 3.6 times as sensitive as one with an L-OO chamber. The sensitivity of the unit was also impacted by whether an ST (short-term) or LT (long-term) electret was selected. When coupled with S chambers, the ST sensitivity is 2.0 Volts/pCi/L/day whereas the LT is rated at 0.15 Volts/pCi/L/day (George, 2011), making the ST slightly more than 13-fold more sensitive. As a result, ST electrets are typically used for short-duration household tests, whereas the LT electrets are advantageous for household tests lasting months. By mixing and matching the two chamber types and two electret types available, there were four different E-PERM® configurations that could be employed. Selection of a configuration was dependent on the expected radon level at the sampling site and the experiment duration. A new electret will be received with a voltage of 700-770 volts, and will give linear response to radon activity down to 200 volts, at which point a new or refurbished electret must be purchased due to loss of linear response (Kotrappa, 1990). So if the chosen configuration was too sensitive, non-linear behavior and untrustworthy output was encountered at worst, and at a minimum excessive and expensive consumption of electret capacity resulted. If the chosen configuration was not sensitive enough, the small change in electret voltage would lead to a large uncertainty associated with the output (CERTI, 2006). The vendor provided a metal pin with each of the L-OO chambers to keep it from being accidentally switched from the off to the on position (or vice versa). This was vital for transport in the caves, where jostling of the chambers is common, but the small pin provided proved difficult to handle when using the switch in the cold, wet, dark environment of the caves. As a consequence, the original pins were replaced by large safety pins prior to cave usage, which functioned suitably in this role. Manipulation of the S-chambers proved simpler, with the only significant problem being that the rotating motion needed to change from on to off sometimes would grab and pinch the Tyvek® envelope, and the resulting chamber was left slightly ajar as opposed to completely closed. This was problematic in cave environments where transport to the surface typically involved an extended period of time in a high-radon environment; Tyvek® pinches thus produced inflated radon measurement as a result, and operators were cautioned about this occurrence and advised to remove the unit from the Tyvek® bag when shutting it off.

A SPER-1E reader was used to read the electret voltages before and after the field trials. Since the electret voltage is a surface voltage only, it cannot be measured in the standard method by touching a lead from a voltmeter to the active surface. The SPER reader is designed to measure the electret charge over a small fixed air gap without contact to the electret surface, which allows electret surface voltage to be calculated. This approach is known as a capacitive probe method (Kotrappa, 1988). The measurement depends on the distance of the through-space gap, which is controlled by the design of the reader. However, changes in temperature and humidity can cause expansion/contraction of the materials, altering this measurement gap. As a consequence, the most accurate results are obtained when temperature values during pre-exposure and post-exposure electret readings are the same, and the reader is used in an environment with relative humidity of less than 75% -- the operating manual suggested using the reader in an air-conditioned space (Rad Elec, 2015). The authors attempted to design SPER methods that could be used accurately in the field, but they were largely unsuccessful, including using a vehicle climate-control system to achieve the desired final temperature, and varying the distance from a wood-burning stove to find that same ideal final temperature. It should be noted that even if a final reading could be taken at a temperature matching that used for the initial reading, this did not ensure that the sensor itself had fully equilibrated to the ambient air temperature after spending several days at cave temperature. As a result, the best practice adopted for using the SPER reader was to read electret voltages in a temperature and humidity controlled laboratory, and requiring at least a 12-hour residence time for the E-PERM® in the laboratory prior to measuring its voltage.

Finally, gamma radiation exposure impacts the electret voltage change, and consequently the radon calculations made by the Winsper software (Rad Elec, 2015). Normally, the E-PERM® responded to ionizing decays produced by gaseous species or their progeny, as non-gaseous species will be prevented from reaching the chamber by a filter. Given the passive nature of gas entry and the scarcity of gaseous radioactive species, most of the signal resulted from radon, and in particular the longer-lived isotope of radon, ^{222}Rn. However, due to the extraordinary penetrating power of gamma radiation, portions of the radiation from external gamma-emitting species in the vicinity will penetrate through the chamber wall, ionizing gases inside the chamber, and creating a voltage drop on the electret. The calculation of the final radon concentration takes the ionization from the local gamma background radiation into account, and its correction is a minor factor in high-radon environments (CERTI, 2006). Most radon measurements in houses are impacted more in a relative sense by the gamma radiation background exposure than in these cave trials, although the background gamma radiation exposures measured have not shown a great degree of variability, and in radon measurements in residences this exposure is often assumed to be a constant value such as a state average (Bogen,

1981) in place of a measured value. The greatest contributors to natural gamma radiation background include ^{40}K and members of the ^{238}U and ^{232}Th decay chains, which produce ^{222}Rn and ^{220}Rn respectively (Pattison, 2009). Even if the high radon levels seen in the study caves were the result of transport and concentration from remote source rock, the gamma radiation from the radon daughter elements (significantly ^{214}Pb and ^{214}Bi from ^{222}Rn, ^{212}Pb, ^{212}Bi, and ^{208}Tl from ^{220}Rn) would make a much more significant contribution to the overall gamma radiation exposure burden, creating higher overall values (Aucott, 2014). Unfortunately, since radon activity has been shown to be highly variable with regard to time and locale within the cave, this means that the contribution to the overall gamma radiation exposure from radon daughter elements will also be variable, making it much harder to estimate average gamma radiation exposure during E-PERM® deployment in the absence of a concurrent experimental measurement. For environmental protection, the gamma ray dosimeters were deployed in the cave within Tyvek® bags, just like the EIC sensors.

Results and Analysis

Many trials were run in northeastern Iowa caves comparing E-PERM® response to that of a continuous radon monitor placed at the same site. No gross variations were observed, with values typically within 10%, similar in magnitude to the variability found when comparing CRM units against each other in the same manner (Welch, 2015). Given this observed preliminary behavior, the E-PERM® response was judged to provide sufficiently accurate response to use them for extensive trials comparing different sites within the same cave.

A series of experiments were undertaken in Coldwater Cave, Winneshiek County, Iowa to illustrate and evaluate some of the issues related to working in a high-radon environment with spatial and temporal radon variability using the E-PERM® sensors. In a nod to the concerns of Bruzzone, it should be noted that this cave is essentially an underground river system and extremely wet and humid, and is also well-known as having a highly-elevated CO_2 level (Koch, 1974). More than 27 km of passage have been mapped in the cave, but the experiment was limited to seven locations spaced evenly along a circa 2-km stretch of the main cave passage (Figure (2)). Since the radon was expected to vary with the season, and the ideal E-PERM® configuration depended on the radon level, two duplicate trials of the experiment were run, one in December 2015 and one in June 2016. Each of the trials tested two different time frames for the sensor, a circa 60-hour experiment (labeled as the A experiment) and a circa 36-hour experiment (labeled as B), with the shorter experiment nested centrally within the longer duration time frame. Since the cave was a 4.5 hour one-way drive from Knox College, the 36-hour time frame represented what could be reasonably undertaken in a weekend, given the constraints of a Mon-Fri 9-5 work schedule. The 60-hour version was selected as something that was thought to be more of an ideal time frame for data quality independent of time constraints from employment. At each of the seven in-cave sampling sites, three different E-PERM® configurations, of the four that were possible, were run side-by-side; the most sensitive configuration with the ST electret and the S chamber was rejected as it was almost certain to be overloaded for all trials. For the three configurations selected for the experiment, Configuration I utilized an LT electret and an S chamber, Configuration II an ST electret and an L-OO chamber, and Configuration III an LT electret and an L-OO chamber. Following sensitivity discussion above, Configuration III was expected to be the least sensitive configuration, whereas Configuration I was expected to be 3.6 times as sensitive and Configuration II 13 times as

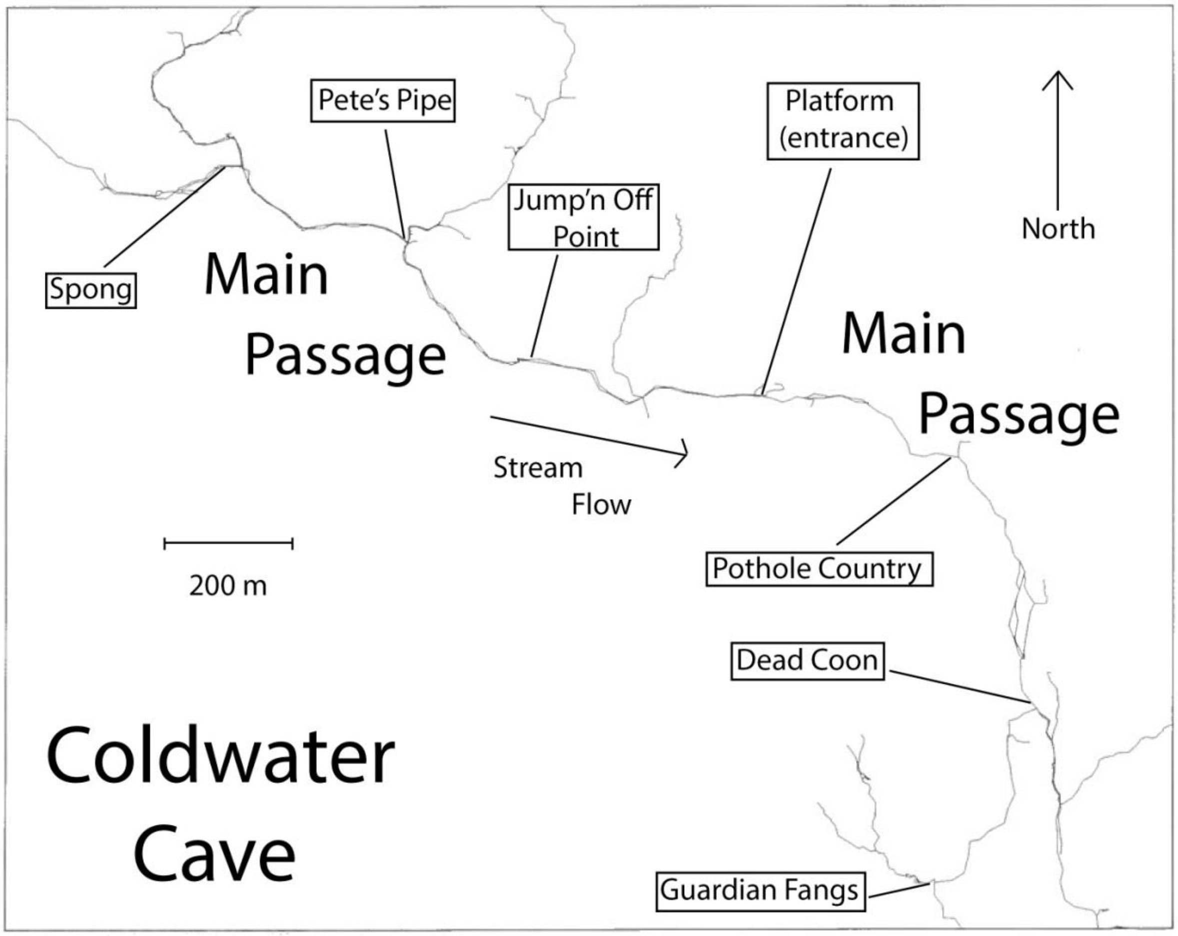

Figure (2): Spatial relationship of sampling sites in Coldwater Cave.

sensitive. All initial electret voltages were read in the climate-controlled laboratory with the electrets fully equilibrated to these conditions (21.1°C in December, 22.8°C in June, low humidity in both cases). After transport and deployment of the sensors in the 7.8°C cave, two versions of the final voltage were measured, one in a bunkhouse adjacent to the cave entrance with no climate control, taken as soon as possible after the sensors emerged from the cave, and a second set read at a later time in the laboratory after full equilibration of the sensors to those conditions.

Configuration III was expected to have the highest uncertainty of the three approaches, based on the fact that it was the least sensitive configuration and would give the smallest electret ΔV value for a given radon level. Thus, the voltage uncertainty present from using the reader would become a greater fraction of the measured ΔV, producing greater relative uncertainty. The Winsper software (Rad Elec, 2015) used equation A1 to calculate uncertainty, and it can be seen that a small ΔV in the denominator of the E2 term will cause it to become large and lead to a larger overall relative uncertainty, especially given that E1 is constant and E3 becomes small in a high-radon environment.

(Eqn. A1) $Et = \sqrt{E1^2 + E2^2 + E3^2}$

Et = total relative uncertainty

E1= error due to uncertainty in component size
= 5% based on experiment by the vendor

E2= error due to uncertainty in electret voltage reading

$$= \frac{100\% * 1.4}{Initial\ voltage - Final\ voltage}$$

E3= error due to gamma radiation exposure uncertainty

$$= \frac{100\% * 0.1}{Radon\ activity}$$

Table (1) summarizes the calculated uncertainties based on the stated relationship with the experimental values. As expected, Configuration III had greater uncertainty than the other two configurations, which were similar in magnitude. The absolute uncertainties in June were larger in proportion to the larger measured radon levels during that time frame. Moving from the 60-Hr to the 36-Hr trial had no impact on the uncertainty of sensors with Configurations I and II, but the low ΔV values measured with Configuration III led to deterioration when the shorter time frame was adopted.

In viewing the calculated radon activities from the triplicate sensors (see Tables (2a) and (2b)), it can be seen that in the majority of sets that the Configuration III radon activity value was relatively close to those yielded by the other two configurations at the given site. However, for every single case where the relative standard deviation of the three sensors at that site was over 10% (7 out of 28 total), it can be seen that the Configuration III sensor result was always very different from the other two values, and always larger. By omitting the Configuration III value, the relative standard deviations of these sets dropped to less than 10% in all cases. Although no "known" values were available to measure accuracy of the sensors in the cave environment, the

Table (1): Uncertainties as a function of E-PERM® configuration.

	December 2015 A Exp 60-Hr 7-site avg	December 2015 B Exp 36-Hr 7-site avg	June 2016 A Exp 60-Hr 7-site avg	June 2016 B Exp 36-Hr 7-site avg
Absolute Uncertainties in pCi/L				
Config I (LT electret, S Chamber)	16.6	17.0	24.2	25.2
Config II(ST electret, L-OO Chamber)	16.7	17.3	25.3	26.2
Config III (LT electret, L-OO Chamber)	29.8	42.7	36.4	50.4
Relative Uncertainties in %				
Config I (LT electret, S Chamber)	5.10%	5.29%	5.05%	5.14%
Config II(ST electret, L-OO Chamber)	5.03%	5.09%	5.02%	5.05%
Config III (LT electret, L-OO Chamber)	7.23%	10.75%	6.55%	8.24%

Table (2a): Radon activity as a function of configuration, December 2015. (** = operator error)

60-Hr Trials, in pCi/L							
	Spong	P. Pipe	Jump'n Off	Platform	Pothole	D. Coon	G. Fangs
Config I (LT electret, S Chamber)	301.8	293.6	296.9	322.9	325.0	323.4	415.2
Config II(ST electret, L-OO Chamber)	338.0	313.0	303.3	336.4	310.6	322.3	398.0
Config III (LT electret, L-OO Chamber)	391.9	451.6	285.4	611.6	331.1	**	405.6
3 config avg	343.9	352.7	295.2	423.6	322.2	322.9	406.3
Config I + II avg	319.9	303.3	300.1	329.7	317.8	322.9	406.6
3 config RSD (%)	13.2	24.4	3.1	38.5	3.3	0.2	2.1
Config I + II RSD (%)	8.0	4.5	1.5	2.9	3.2	0.2	3.0
36-Hr Trials, in pCi/L							
	Spong	P. Pipe	Jump'n Off	Platform	Pothole	D. Coon	G. Fangs
Config I (LT electret, S Chamber)	275.6	277.7	279.3	321.5	316.6	343.9	434.6
Config II(ST electret, L-OO Chamber)	304.4	321.1	281.7	332.6	353.9	312.0	476.1
Config III (LT electret, L-OO Chamber)	692.7	285.9	320.8	348.9	290.6	350.6	488.3
3 config avg	424.2	294.9	293.9	334.3	320.4	335.5	466.3
Config I + II avg	290.0	299.4	280.5	327.1	335.3	328.0	455.4
3 config RSD (%)	54.9	7.8	7.9	4.1	9.9	6.1	6.0
Config I + II RSD (%)	7.0	10.2	0.6	2.4	7.9	6.9	6.4

data in Tables (2a) and (2b) suggest that Configuration III yielded output that was less accurate overall in addition to having a higher uncertainty. As such, the site averages using only Configurations I and II were considered to be better measures of the actual cave conditions.

Comparing the Configuration I results vs. the Configuration II output in Figures (3a) and (3b), the differences were small and typically within the uncertainties of the individual readings. The average of the Configuration I-Configuration II duo relative standard deviations was 3.7% for the60-Hr sets, and 5.5% for the 36-Hr sets, with none exceeding 10.5%. The nearness of the responses between Configurations I and II might suggest that each would work equally well in a cave experiment, but other factors must be taken into account prior to making a final decision. Configuration I utilized S chambers, which, as noted previously, have a greater volume by a factor of 3.6 than the L-OO chambers used in Configuration II. This makes a big difference in terms of the pack space required to transport multiple sensors. A single experimentalist might be able to walk through a cave comfortably with 7-8 S chambers, but for any kind of transport through more difficult passage involving climbing, crawling, stooping, or swimming, 4-5 S chambers would be a safer burden. In prior trials using L-OO chambers, transporting a dozen

Table (2b): Radon activity as a function of configuration, June 2016

60-Hr Trials, in pCi/L							
	Spong	**P. Pipe**	**Jump'n Off**	**Platform**	**Pothole**	**D. Coon**	**G. Fangs**
Config I (LT electret, S Chamber)	518.3	721.5	599.3	495.8	423.3	283.6	307.4
Config II(ST electret, L-OO Chamber)	545.4	756.9	613.2	519.5	462.3	309.3	323.5
Config III (LT electret, L-OO Chamber)	543.0	794.4	665.9	705.2	2213.2	340.2	291.1
3 config avg	535.6	757.6	626.1	573.5	1032.9	311.0	307.3
Config I + II avg	531.9	739.2	606.3	507.7	442.8	296.5	315.5
3 config RSD (%)	2.8	4.8	5.6	20.0	99.0	9.1	5.3
Config I + II RSD (%)	3.6	3.4	1.6	3.3	6.2	6.1	3.6
36-Hr Trials, in pCi/L							
	Spong	**P. Pipe**	**Jump'n Off**	**Platform**	**Pothole**	**D. Coon**	**G. Fangs**
Config I (LT electret, S Chamber)	480.8	714.6	634.5	530.8	446.3	290.4	328.8
Config II(ST electret, L-OO Chamber)	543.1	786.0	648.4	512.8	517.2	307.4	321.2
Config III (LT electret, L-OO Chamber)	1147.5	777.5	690.1	530.8	505.2	299.0	326.5
3 config avg	723.8	759.4	657.7	524.8	489.6	298.9	325.5
Config I + II avg	512.0	750.3	641.5	521.8	481.8	298.9	325.0
3 config RSD (%)	50.9	5.1	4.4	2.0	7.8	2.8	1.2
Config I + II RSD (%)	8.6	6.7	1.5	2.4	10.4	4.0	1.7

sensors per person through difficult passage has been accomplished without duress. Whereas size favors Configuration II, cost concerns favor Configuration I. When purchased, the electrets used in this work had an average initial voltage of 749V. As they were exposed to ionizing radiation, this voltage dropped toward zero. However, the electret loses linear response at 200V, so this value defined the lower limit of the working range of the electret. So the working voltage capacity averaged 549V, and the sensors cost $25 when purchased new (ignoring shipping costs and taxes here). From the ΔV measured during each cave trial, one can determine the amount of the electret capacity exhausted, and the associated cost; all shown on Table (3). The Configuration II trials cost almost twice as much for a given experimental duration. If cost is not a concern, Configuration II is probably the best approach for the 36-Hr experiments. For the 60-Hr trials, the Configuration II cost was still nearly double that of Configuration I, but there were

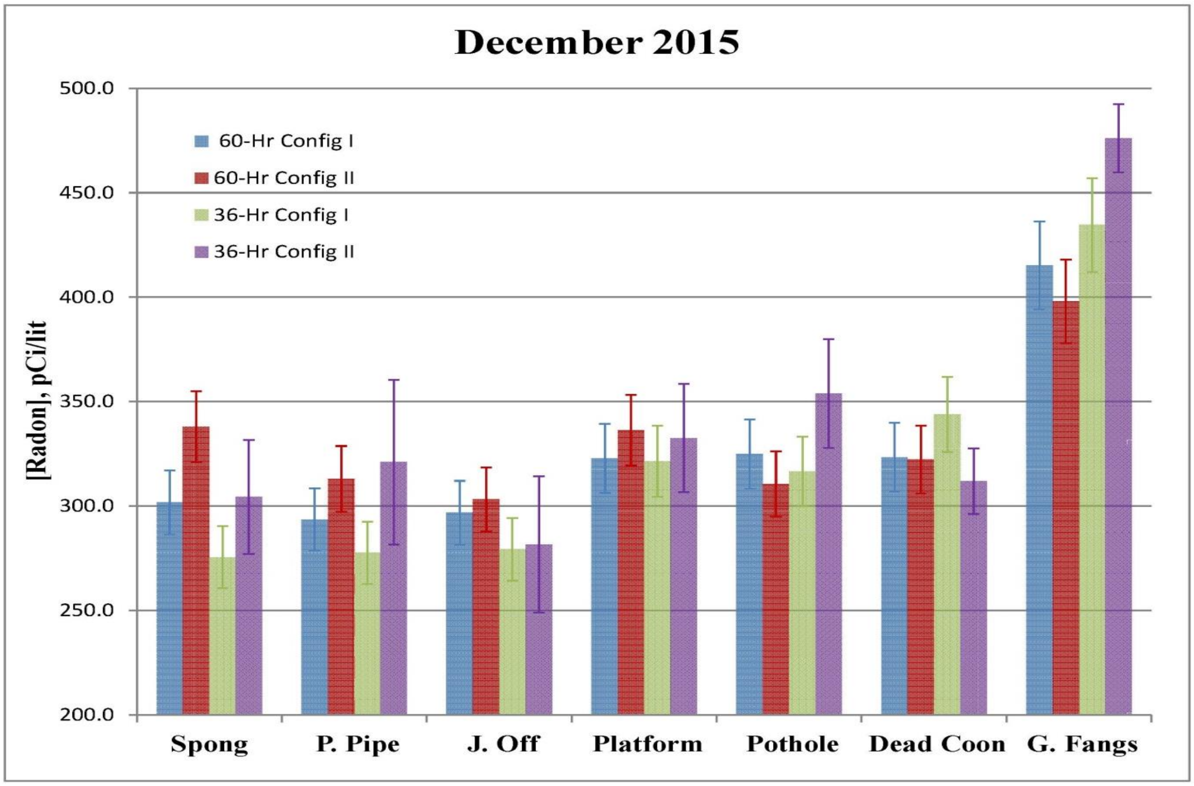

Figure (3a): Radon activities with uncertainties, December 2015.

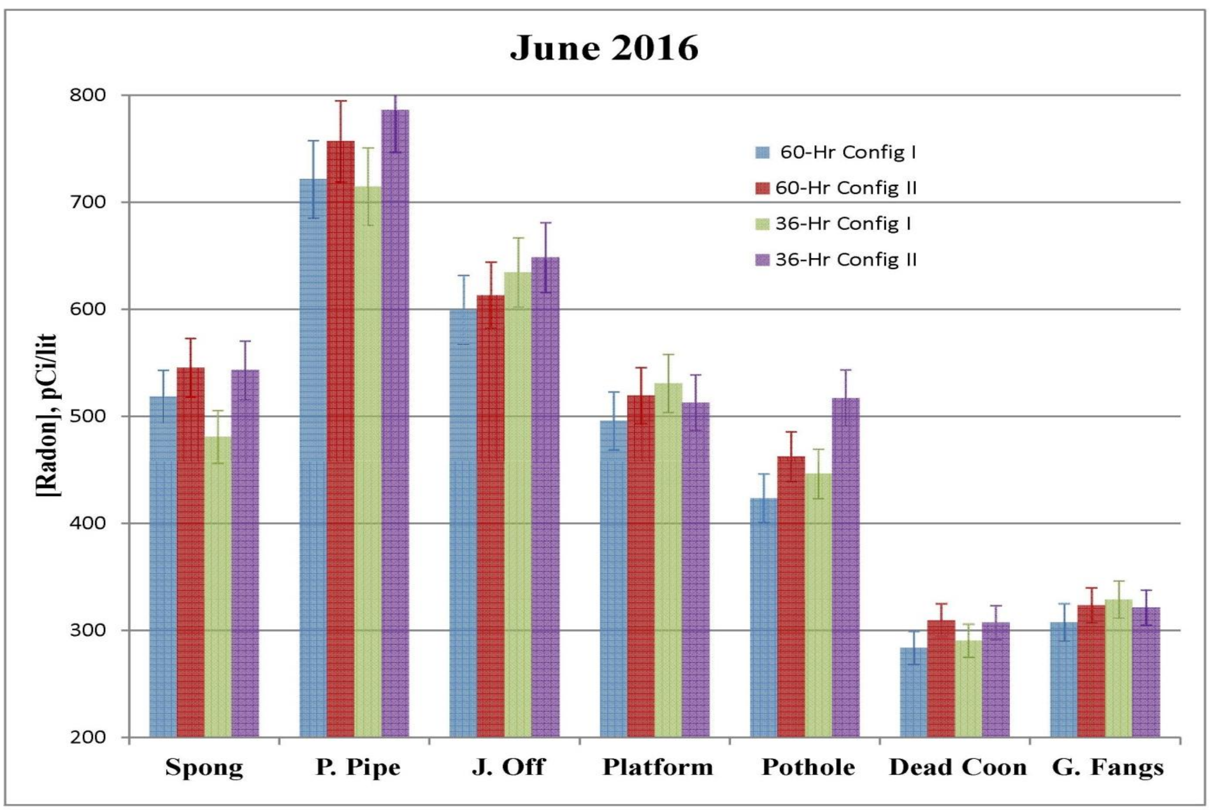

Figure (3b): Radon activities with uncertainties, June 2016.

Table (3): Capacity consumption and cost for the different E-PERM® configurations.

	Dec 2015 60-Hr 7-site Avg	Dec 2015 36-Hr 7-site Avg	June 2015 60-Hr 7-site Avg	June 2015 36-Hr 7-site Avg
ΔV Config I (LT electret, S Chamber)	142	82	206	122
ΔV Config II (ST electret, L-OO Chamber)	247	151	361	217
ΔV Config III (LT electret, L-OO Chamber)	23	15	48	22
Cost Config I (LT electret, S Chamber)	$6.47	$3.75	$9.39	$5.55
Cost Config II (ST electret, L-OO Chamber)	$11.25	$6.87	$16.42	$9.89
Cost Config III (LT electret, L-OO Chamber)	$1.06	$0.68	$2.20	$1.00

also concerns about the capacity of the electrets and the risk of overloading them. One of the June 2015 60-Hr trials had a ΔV of 528V – nearly the complete capacity of a new sensor. If the radon activity had been a little bit higher (which had been observed before), the electret final voltage would have dropped below 200V into the non-linear response range, and the data point rejected. Since each experiment required a significant amount of time/money/energy commitment, and the radon activities were hard to project accurately in advance, an experimentalist will tend to err on the cautious side and try to not come close to going into the non-linear range. So for this cave, Configuration II seems too risky for 60-Hr trials, and Configuration I is preferable. Although perhaps not an elegant experimental design, given their comparable output, it should be reasonable to run trials and pool results from experiments featuring a mix of Configuration I and Configuration II probes.

From viewing Figures (3a) and (3b), the short-term variability of radon activities was clearly small in this cave, as the 36-Hr duration trials were very similar to those from the 60-Hr trials. The same cannot be said for the long-term variability, as comparison of the December vs. June data illustrates. Not only were the values themselves very different, the upstream/downstream trends (upstream to downstream is left to right in the figures, with roughly even spacing of 350m between sites) were reversed. Explanation of this phenomenon is the subject of ongoing research in this group.

Figure (4) shows the impact of reading the voltage with the SPER reader after equilibration in a temperature and humidity controlled environment, as opposed to taking readings in the field in a less controlled environment. The changes were not dramatic, but most commonly involved the electret voltage rising a few volts between the initial and equilibrated reading. Table (4) relates how these changes impacted the final readings in units of pCi/L. The effect was inversely proportional to the ΔV measured during the trial, with the largest issue seen for Configuration III, the least sensitive of the group. The more sensitive configurations were impacted only slightly, given the very large radon activities measured in this study. Changes of this magnitude would be much more of an issue for measurements in residences.

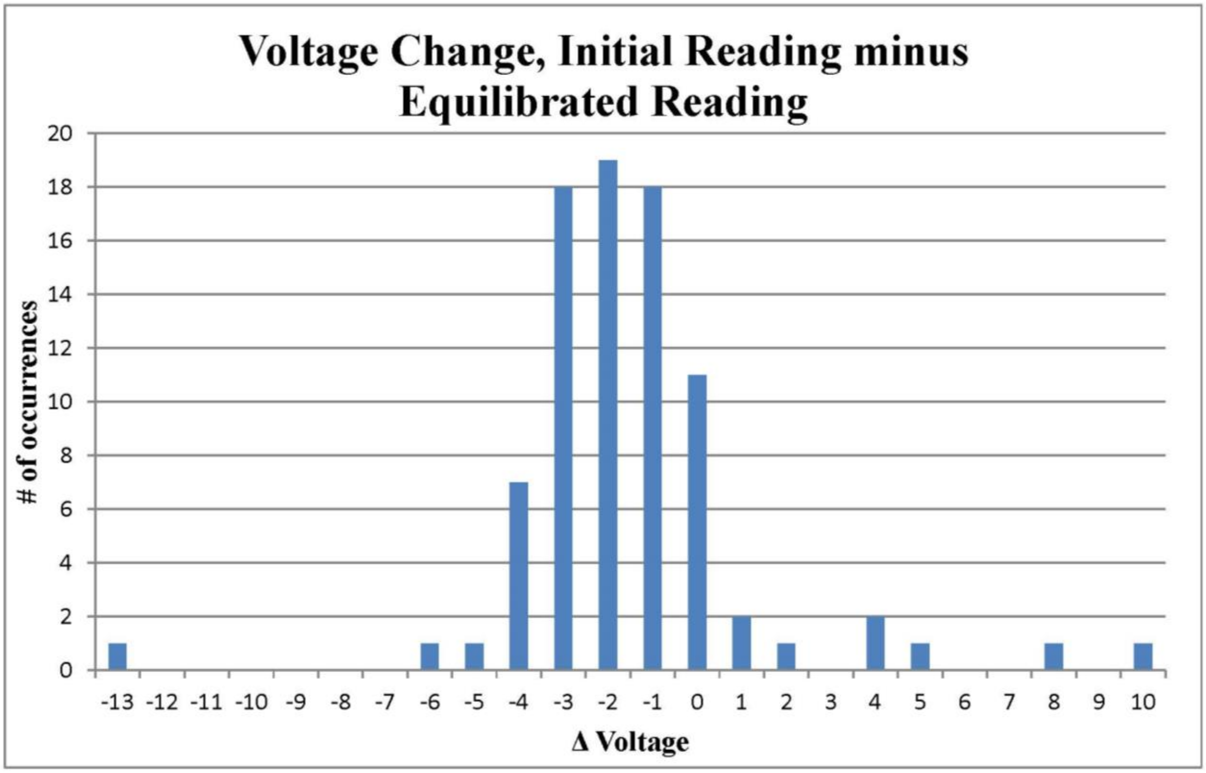

Figure (4): Voltage change, initial minus equilibrated reading, pooling December 2015 and June 2016 trials.

Readings of gamma radiation background are shown in Table (5). Since fewer of these sensors were available, the pool of readings was somewhat sparse; a compendium of all readings from these Coldwater Cave sites is given at the top of the table. Clearly, great variability has been observed, and it looks as if the values change in concert with radon activities: they differ at the seven different sites within the cave, and differ with the season. Further work is needed to be able to predict their value at a given location at a given time. For the purposes of this study, the "Best Values" set was used for all of the prior calculations, which are listed in Table (5) along with a set of "Alternative Values". The "Alternative Values" were found by averaging all values in the November – February time frame and applying these to the December 2015 data set, and averaging all the May-July values and applying this average to the June 2016 data set.

Table (4): Deviation in radon activity outcome due to SPER reader environment and equilibration time, pooling December 2015 and June 2016 trials.

	Average Deviation, pCi/L from Initial to Equilibrated
Config I (LT electret, S Chamber)	6.9
Config II(ST electret, L-OO Chamber)	2.6
Config III (LT electret, L-OO Chamber)	29.6

Table (5): Gamma radiation background values by site and date, in μR/Hr.

Compendium of All Values	**Spong**	21.0, Nov 2012	34.6 July 2016
	Pete's Pipe	40.3, July 2012	72.1, July 2016
	Jump'n Off Point	18.0, Dec 2012	15.8 Jan 2013
	Platform	16.7, Feb 2012	83.9 July 2016
	Pothole Country	53.8, May 2013	98.9, July 2016
	Dead Coon	25.1, June 2016	
	Guardian Fangs	24.7, June 2016	
Best Values	**Spong**	21.0	
	Pete's Pipe	40.3	
	Jump'n Off Point	16.9	
	Platform	16.7	
	Pothole Country	53.8	
	Dead Coon	25.1	
	Guardian Fangs	24.7	
Alternative Values		**Dec 2015**	**June 2016**
	Spong	17.9	54.2
	Pete's Pipe	17.9	54.2
	Jump'n Off Point	17.9	54.2
	Platform	17.9	54.2
	Pothole Country	17.9	54.2
	Dead Coon	17.9	54.2
	Guardian Fangs	17.9	54.2
Iowa Average (Bogen, 1981)	7.5		

Calculations using the "Alternative Values" were made and compared to determine the impact of gamma radiation background exposure variations on the calculated radon activity. Different radon activity values result, but as can be seen in Table (6), the changes were small. No extreme outliers were present, and all of the relative uncertainties seen from changing the gamma radiation exposure between the two schemes produced relative uncertainties in calculated radon activity of less than 1.6%.

Conclusions

E-PERM® EIC sensors have shown themselves to be well-suited for operation in cave environments. Coldwater Cave is particularly wet and has very high CO_2, but the EIC sensors produced comparable output to continuous radon monitors. Precautionary protocols involving barrier bags during transport and measurement were enlisted to protect the sensors from water, dust, and physical shock, and are recommended to avoid some of the problems reported by prior investigators. Selection of the appropriate sensor configuration was important, being a function

Table (6): Average deviation in calculated radon activity (in pCi/L) from use of differing gamma ray background readings.

	average deviation best - alternative pCi/L
December 2015	
Config I (LT electret, S Chamber)	0.9
Config II(ST electret, L-OO Chamber)	1.3
Config III (LT electret, L-OO Chamber)	1.4
June 2016	
Config I (LT electret, S Chamber)	0.9
Config II(ST electret, L-OO Chamber)	1.3
Config III (LT electret, L-OO Chamber)	1.4
Overall	
Config I (LT electret, S Chamber)	0.9
Config II(ST electret, L-OO Chamber)	1.3
Config III (LT electret, L-OO Chamber)	1.4

of the duration of the experiment and the radon level at the site. Whereas the duration can be controlled, the cave radon level cannot, is variable, and its magnitude will be unknown at the outset of an experiment. Past experiments will give some predictive ability, but the information needs to be specific regarding the particular sites in the cave and the time of year. When starting work in a new cave, the lack of this prior information regarding radon activity will make it very difficult to gauge the proper E-PERM® configuration; a preliminary trial would be advisable to provide guidance.

Configuration III, the least sensitive of the configurations tested in this work, showed poor accuracy and high uncertainty, and it was the most susceptible to impact from use of the SPER reader to measure a voltage in the field of any of the configurations tested. Although it would be easy to reject this configuration for cave use, there was nothing inherently wrong with it, as all of the observed limitations likely resulted from the small ΔV measured in these trials. If an experimentalist was constrained to working on the weekends and decided to undertake a 7-day trial in this same cave (place sensors one weekend, pick up the next), Configuration III would likely be the best approach as it would produce a much larger ΔV, whereas the other two configurations would probably discharge the electret completely during this time frame.

Configuration I and Configuration II both gave comparable results for this work. Configuration I used larger chambers that are problematic if a large number need to transported through the cave per person. It also featured smaller ΔV values than Configuration II, meaning there was less expense per trial and less inherent risk of complete electret discharge during an experiment. For longer exposures as in the 60-Hr study, the risk of discharging electrets supersedes other concerns, and Configuration I is recommended. For shorter exposure durations, as in the 36-Hr study, Configuration II is preferable mainly based on the smaller size of the chambers.

Using the SPER reader in the field did not have a significant impact on the output compared to measurements acquired in a climate-controlled laboratory if the voltage change was large (>50V) and the radon concentration high (>200 pCi/L). Given the hassle of transporting and using the SPER reader in the field, it is preferable to use this approach only when necessary (e.g. sequential field trials with the same electrets) and when a locale with humidity of less than 75% can be found. Cave gamma radiation exposures measured in this study have considerably higher values than the state average often used for measurements in houses. Unless gamma background exposures are going to be measured concurrently along with radon activity at each sampling site, one needs to be able to predict its value based on past data. Further work is needed to develop a systematic scheme to predict values for Coldwater Cave, but the shortcoming of not having a systematic correction was mitigated by the fact that the uncertainty in the gamma radiation exposure value converted to only a tiny correction in the calculated radon activity.

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References

Aucott, T. J., 2014. Gamma-Ray Background Variability in Mobile Detectors. Ph.D. Thesis, Nuclear Engineering, UC Berkeley, USA. http://escholarship.org/uc/item/2ph593s2#page-1. Accessed 21 July, 2016.

Bauser, H., and Ronge, W., 1978. The Electret Ionisation Chamber: a Dosimeter for Long Term Personnel Monitoring. Health Physics, 34, 97-102.

Bogen, K.T., and Smith, A.S., 1981. Population Exposure to External Natural Radiation Background in the USA. EPA Report ORP/SEPD-80-12.

Bruzzone, D., Bussallino, M., Castello, G., Maggiolo, S., and Rossi, D., 2006. Measurement of the Concentration of Radon Gas in the Toirano's Caves (Liguria). Annali di Chimica, 96, 515-524.

CERTI (Center for Environmental Research and Technology), 2006. Becoming Proficient with Rad Elec E-PERM® Measurement Devices.

Cigna, A.A., 2005. Radon in Caves. International Journal of Speleology, 34(1-2), 1-18.

Fjeld, R.A., Montague, K.J., Haapala, M.H., and Kotrappa, P., 1994. Field Test of Electret Ion Chambers for Environmental Monitoring. Health Physics, 66(2), 147-154.

George, A.C., and Bredhoff, N., 2011. Current State of the Art in Measuring Environmental Radon. Proceedings of the 2011 International Radon Symposium, pp. 36-44. http://aarst-nrpp.com/proceedings/2011/Current State of the Art in Measuring Environmental Radon.pdf. Accessed 20 July 2016.

Koch, D.L., and Case, J.C., 1974. Report on Cold Water Cave. Iowa Geological Survey Report Submitted to the Governor of Iowa.

Kotrappa, P., Dua, S.K., Gupta, P.C., and Mayya, Y.S., 1981. Electret – A New Tool for Measuring Concentrations of Radon and Thoron in Air. Health Physics, 41, 35-46.

Kotrappa, P., Dempsey, J.C., Hickey, J.R., and Stieff, L.R., 1988. An Electret Passive Environmental ^{222}Rn Monitor Based on Ionization Measurement. Health Physics, 54(1), 47-56.

Kotrappa, P., Dempsey, J.C., Ramsey, R.W., and Stieff, L.R., 1990. A Practical E-PERM™ (Electret Passive Environmental Radon Monitor) System for Indoor ^{222}Rn Measurement. Health Physics, 58(4), 461-467.

Kotrappa, P., and Stieff, L., 1994. The Measurement of Very High Levels of ^{222}Rn Concentrations using Electret Ion Chambers. Proceedings of the 1994 International Radon

Symposium, pp. 1-6. http://aarst- nrpp.com/proceedings/1994/The Measurement of Very High Levels of Radon Concent.pdf. Accessed 22 July 2016.

Marvin, H. B., 1955. How to Measure Radiation with Electrets. Nucleonics, 13, 82-92.

Nemangwele, F., 2005. Radon in the Cango Caves. M.Sc. Thesis, Department of Physics, University of the Western Cape, South Africa. http://etd.uwc.ac.za/xmlui/bitstream/handle/11394/231/Nemangwele_MSC_2005.pdf?sequence=1. Accessed 25 July 2016.

Pattison, J.E., Hugtenburg, R.P., and Green S., 2009. Enhancement of Natural Background Gamma-Radiation Dose around Uranium Microparticles in the Human Body. Journal of the Royal Society Interface, 7(45), pp. 603-611. DOI: 10.1098/rsif.2009.0300. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2842777/. Accessed 21 July 2016.

Rad-Elec, 2015. *Quick Start Manual*, Version 2.321i.

Stieff, A., Kotrappa, P., and Stieff, F., 2012. The Use of Barrier Bags with Radon Detectors. Proceedings of the 2012 International Radon Symposium, pp. 67-79. http://aarst-nrpp.com/proceedings/2012/The Use of Barrier Bags with Radon Detectors.pdf. Accessed 20 July 2016.

Welch, L.E., Paul, B.E., and Jones, M.D., 2015. Measurement of Radon Levels in Caves: Logistical Hurdles and Solutions. Proceedings of the 2015 International Radon Symposium, pp. 1-17. http://aarst-nrpp.com/proceedings/2015/Measurement of Radon Levels in Caves: Logistical Hurdles and Solutions.pdf. Accessed 20 July 2016.