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CONCLUSION OF A MULTI-YEAR STUDY ON THE ELEVATION EFFECTS ON SCINTILLATION CELL COUNTING EFFICIENCY FOCUSING ON THE PYLON™ MODEL 300

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Abstract

This is a continuation of a study begun in 2005 when the authors first reported on the theoretical possibility of a non-trivial error in calibration of radon chambers caused by the current use of scintillation cells. The ramifications of this error are just now being felt by the radon industry as experts around the world attempt to better define radon concentration standards and insist upon measurement results more accurate than the traditional 25 %. In this report, the authors conclude their study by comparing the theoretical error and the actual experimental error of using a certain popular scintillation cell made by Pylon™[(1)] with a volume of 271 ml. A graph is presented which predicts the cell calibration error, as a function of the difference in elevation of any secondary chamber and the primary calibration facility, which would be introduced using this Pylon™ cell. The authors summarize their study by presenting a second graph that predicts the cell calibration error introduced by using any right cylinder scintillation cell of any dimensions that can be modeled as a scaled-up or scaled-down version of the popular Rocky Mountain Glassworks cell.

Background

Both theoretical and experimental investigations indicate that the performance of scintillation cells varies when filled at different elevations, as a result of the dependency of alpha particle range on air density (*George, 1983;Eberline 1987; Burkhart, 2005*). In fact, it has previously been shown that this discrepancy in cell counting efficiency for the popular Rocky Mountain scintillation cell[(2)] (a right cylinder cell, 7 cm in diameter and 9.7 cm long, 360 ml in volume) can cause calibration errors between different elevations in the U.S. as large as 9.1% (*Burkhart, 2006*). As the specific cell geometry influences the magnitude of this error, correction factors must be determined for other cells, cells that are not simply scaled-up or scaled-down versions of the Rocky Mountain cell. This study investigates, therefore, the error in cell counting efficiency at different elevations for the Pylon™ Model 300 scintillation cell, using the same apparatus as was used in the earlier Rocky Mountain cell study.

(1) Pylon Electronic Development Company, Ltd., 147 Colonnade Road, Ottawa, Ontario, Canada.
(2) Rocky Mountain Scientific Glass Blowing Co., 4900 Asbury Ave., Denver, CO 80222

Theoretical Considerations

Alpha particles are the type of radiation emitted from ^{222}Rn and two of its decay products: ^{218}Po and ^{214}Po. It is well understood that the range (R) of an alpha particle traveling in air is inversely proportional to the air density (ρ):

$$\rho_l R_l = \rho_h R_h \;, \qquad \text{(Equation 1)}$$

which means that alpha particles travel further at higher elevations (denoted by an "*h*" subscript) where the air is "thinner" (*Lapp, 1963)*. For example, the alpha particles that are emitted by ^{222}Rn, ^{218}Po and ^{214}Po travel more than 20% further in Colorado Springs, Colorado, which is at 6000 feet elevation, than they do at sea level. Alpha particles that are traveling within a scintillation cell may, therefore, strike the interior of a cell which is filled at a high elevation when they would be quenched within the cell air volume, not striking the scintillator, when the same cell is filled at a low elevation.

However, despite having such a significant impact on alpha particle path length, the influence of differing air densities due to elevation has on alpha particle path is not incorporated into current scintillation cell calibration techniques. An important example of why this cell calibration error is commonly ignored can be best understood by following the process by which secondary laboratories calibrate their chambers to the U.S. EPA's primary facility in Las Vegas, Nevada (elevation of approximately 2,200 feet). Briefly, the EPA sends a sample of radon from their chamber (using a standard grab sampling method with a scintillation cell) to one of the secondary locations for analysis. After analyzing the sample, the secondary location can then adjust its calibration factor for the cell/counting system such that their equipment will report the same radon concentration as the EPA. Indeed, this technique has proven very effective, as it allows the secondary locations to read subsequent cell samples from Las Vegas to within a few percent of the target value. In addition, as long as cells that are filled by a secondary chamber (subsequent to calibration) are sent only to other secondary chambers that have also calibrated with the EPA with a cell with identical geometry, all such secondary chambers will agree on the radon concentration within the cell. Thus, any intercomparison between secondary chambers (which are all calibrated with the EPA chamber using this cell geometry) will not uncover any underlying problems attributable to the air density within the cell. The authors are convinced that this is the reason that the problems caused by using grab cells as an intercomparison have not received much attention in the past. Nonetheless, problems do exist and will show up under some circumstances, causing as much as a 9 % to 10 % error.

Specifically, the resultant calibration factors (counts per minute divided by decays per minute; cpm/dpm) that the secondary facilities force onto their systems are dependent upon the radon/air mixture **and the difference in air pressure** between the Las Vegas chamber and the location of the secondary chamber. Errors will become evident when the cell is refilled at the secondary location (if it is at a different elevation than Las Vegas), and is subsequently used to calibrate a radon instrument or a tertiary chamber because the number of decays per minute necessary to achieve a desired counts per minute will change from the earlier calibration, depending upon the difference in elevation between Las Vegas and the secondary chamber. In other words, the cell calibration, cpm/dpm, will be incorrect for the subsequent fill. Clearly, secondary chambers at a high elevation will require less radon (smaller dpm) to achieve the same cpm compared to a chamber at lower elevation.

Experimental Procedure

In order to fill scintillation cells in a way which duplicated the elevations of Las Vegas and other locations (from sea level to 6000 feet), a 25-liter tedlar(3) bag that is typically used for transporting radon was filled over a 12-minute interval from a commercial radon source manufactured by Pylon™. The bag was placed in a large metal cylinder (40 cm diameter and 150 cm length), which was then sealed for a pressure tight fit. The chamber, with the radon bag inside of it, was then brought to one of four pressures by pumping in outside air. The pressure was read by a digital gauge and maintained to within 0.01 pounds per square inch (psi) of the desired value through the use of a pressure regulator. While held at the desired pressure, radon was extracted from the bag at a rate of 5 SCFH (2.4 L/min), and passed through the scintillation cell for four minutes. Before entering the cell, the decay products that had accumulated in the radon bag were filtered out. The valve located at the exhaust port of the cell was then closed, and the cell was allowed to equilibrate with the pressure of the chamber/bag for one minute. See figure1:

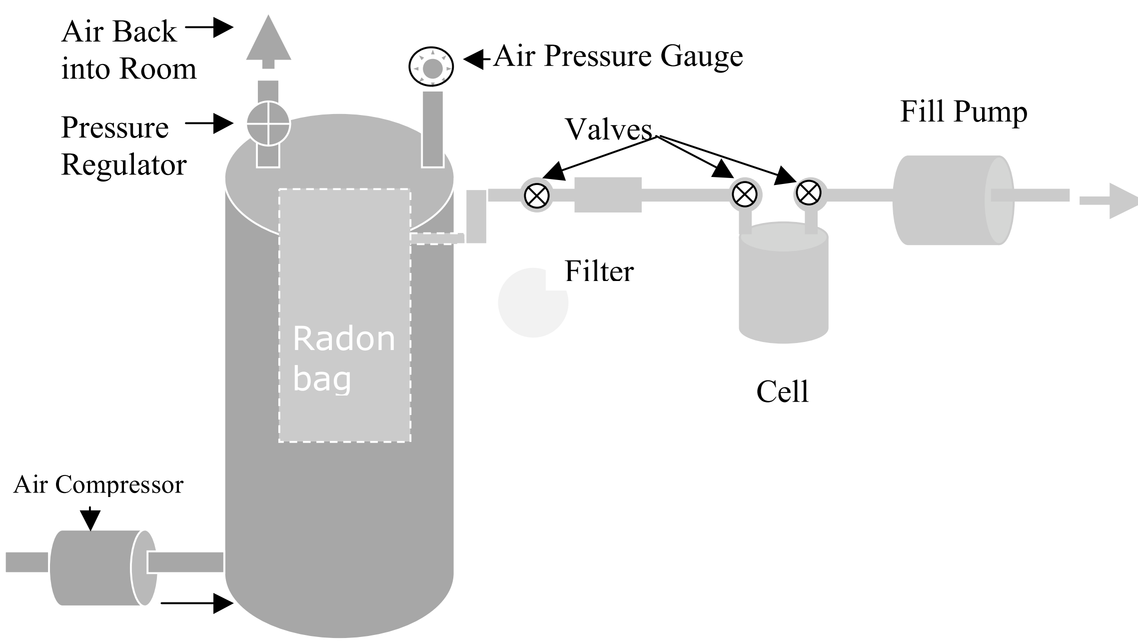

Figure (1): An air compressor brings the chamber to a desired pressure. The pressure is maintained to within 0.01 pounds per square inch with a gauge and a regulator. Using a second, independent pump, the radon is extracted from the bag (under pressure), filtered, and passed through the Pylon™ cell.

(3) Tedlar bags purchased from Environmental Measurements, Inc. 215 Leidesdorff St., San Francisco, CA 94111 and SKC Inc., 863 Valley View Road, Eighty Four, PA 15330-9613, www.skcinc.com.

The same cell was filled sequentially at ambient pressure (820 hPa) in Colorado Springs (6,000 feet above sea level), an over-pressure of 1 psi (888 hPa, equivalent to 4,000 feet above sea level), an over-pressure of 2 psi (957 hPa, equivalent to 2,000 feet above sea level), and an over-pressure of 3 psi (1026 hPa, roughly equivalent to sea level). The cell was flushed between samples, and the background was re-established for each run. Two correction factors were incorporated into the calculations in order to eliminate confounding errors. Specifically, the loss of radon due to radioactive decay during the time between filling the bag and taking samples was accounted for. Also, when sampling at higher pressures, the increased density of air/radon that entered the cell was corrected for by multiplying by the ratio of the ambient pressure divided by the chamber pressure (according to the ideal gas law).

Results

Each “run” is defined as a minimum of two fills of a cell: the first fill was done under one of the three over-pressures and the second fill, using the same cell and the same radon in the bag, was done at ambient pressure. A minimum of five runs was completed at each “elevation” below 6000 feet and at ambient pressure (6000 feet elevation), so that a percent error in counting efficiency could be calculated. Considerable difficulty was encountered because of frequent small holes occurring in the tedlar bags causing leaks, especially when the bag was under pressure; many runs had to be repeated. In addition, the bag only held enough radon to measure the error at two or three “elevations” per run. As a consequence, missing values are represented by “X’s” in table 1, below.

Run Number	***Error at Sea Level***	***Error at 2000’***	***Error at 4000’***	***Error at 6000’***
1	X	0.05	X	0.00
2	X	0.03	-.02	0.00
3	0.08	0.07	X	0.00
4	X	X	.04	0.00
5	X	0.00	-.05	0.00
6	X	0.08	.08	0.00
7	0.04	X	X	0.00
8	0.09	0.07	X	0.00
9	0.04	X	0.07	0.00
10	0.11	X	0.03	0.00
11	X	X	0.04	0.00
12	X	X	0.03	0.00
13	X	X	0.04	0.00
14	X	X	0.02	0.00
15	X	X	0.02	0.00
16	X	X	0.03	0.00
Average +/- σ	0.072 +/- .031	0.050 +/- .030	0.027 +/- .037	0.00
Renormalized	0.00 +/- 0.00	0.025 +/- .030	0.050 +/- .037	0.078 +/- .031

Table (1): Chart of errors in counting efficiency at different elevations found experimentally for the Pylon™ Model 300 scintillation cell. The errors were calculated using Equation 2, found below. The final row shows the renormalized errors calculated using an error of zero for sea level. See comments section.

The errors in table 1 were initially calculated by defining the error on the counting efficiency at 6000 feet elevation as zero error where cell counting efficiency is here defined as cpm/dpm and the number of decays per minute was held constant for any one run (shown as one row in table 1). Radon was held constant by using radon from the same bag, hence, once corrected for half-life decay, the radon was identical for each run. Since the dpm/cell volume was, thereby, held constant (after correcting for the air volume changes at different pressures) the dpm term in the cell calibration cancels out for each run and only the cpm needed to be compared. Therefore, after counting for 60 minutes, the number of counts (corrected for decay and pressure) at 6000 feet (N_h) was compared to the number of counts (corrected for decay and pressure) at the respective lower elevations (N_l). Thus:

$$\text{Error} = \frac{N_h - N_l}{N_h} \quad \text{(Equation 2)}$$

These are the values shown in the second to the last row in table 1. In the previously published theoretical model (*Burkhart, 2005*), however, the error was calculated by dividing by N_l instead of N_h as is done in equation 2 above. However, to minimize incidents of tedlar bags leaking, it was experimentally adventitious to always perform a run at ambient pressure (6000 feet) and finding N_h instead of an over-pressure of 3 psi (sea level) which would have allowed us to find N_l. Therefore, we were able to ascertain a value of N_h for each and every run, making division by N_h more practical than division by N_l, which was frequently not available. Then, in order to more easily compare to previous theoretical and experimental results, all of the error values were renormalized by forcing the error at sea level to be 0 % and correcting the other errors accordingly. These are the values shown in the last row of table 1. (See the simple equation used for renormalization in the comments section at the end of this paper).

Discussion of Results

There is an error, linear with elevation, when comparing cells filled at sea level with cells filled at other elevations, with the error maximizing at .078 (7.8 %) for cells filled at 6000 feet elevation. This latter result agrees reasonably well with the theoretical prediction(4) shown for the Pylon™ cell in table 2, below.

Cell Manufacturer	Cell diameter	Cell length	Theoretical Error
EDA	5.3 cm	7.5 cm	8.0 %
Pylon™	**5.3 cm**	**13 cm**	**8.8 %**
Rocky Mountain	7.0 cm	9.7 cm	9.8 %

Table (2): Chart of theoretical differences in counting efficiency between cells used at sea level and at 6000 feet of elevation. The theoretical errors are defined as the Error = 1 – (N_h-N_l)/N_l.

In addition, the results confirm the qualitative expected dependence of this error on cell geometry: the error found here for the Pylon™ Model 300 cell is less than that of the

(4) The numerical analysis leading to this theoretical prediction, done by Robert E. Camley at the University of Colorado-Colorado Springs, can be found in our earlier work (Burkhart, 2005).

Rocky Mountain cell. We believe this smaller error arises from the relative dimensions between the two types. Specifically, the Pylon™ Model 300 has a relatively smaller diameter compared to its length than the Rocky Mountain. (The ratio of the diameter to the lengths for the Pylon^{TM} Model 300 is 0.41, while that of the Rocky Mountain is 0.72.) As previously discussed (Burkhart, 2005), the narrow profile of the Pylon™ Model 300 lessens the extent to which the difference in alpha particle range at different air densities affects counting efficiency.

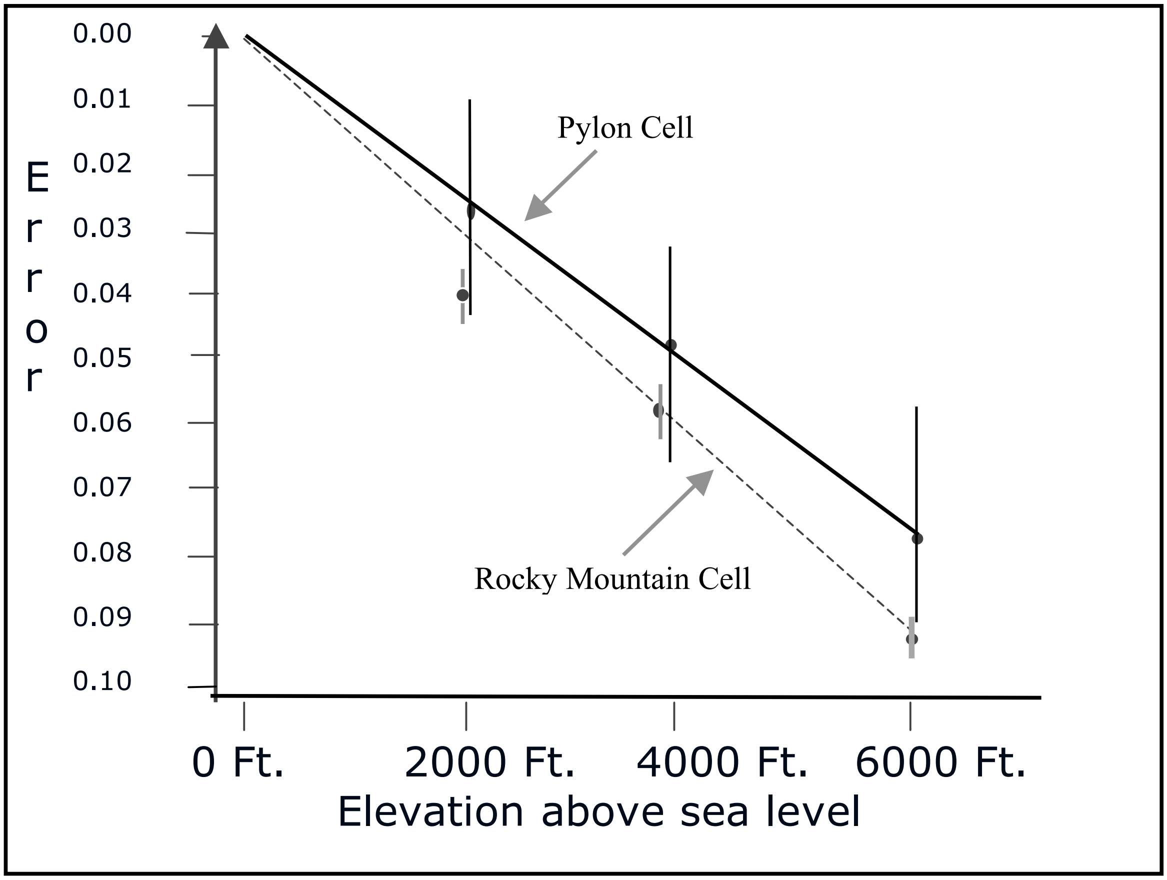

Figure (2) This graph shows the error introduced by using the Pylon^{TM} cell for calibration of secondary chambers. The maximum error between two chambers occurs when both chambers calibrate to the Las Vegas U.S. EPA radon chamber while one chamber is at sea level and the second is at 6000 feet above sea level. That error is 0.078, or 7.8 %. With the Rocky Mountain cell, that same maximum error was found to be around 9.1 %, once renormalized to sea level (Burkhart 2006).

Secondary chambers, which used either the Pylon™ cell or the Rocky Mountain cell for their calibration with the U.S. EPA, can use figure 2 in order to correct their reported radon to represent the "true" radon in their chamber when exposing a radon instrument or when calibrating a tertiary chamber. By "true" radon, we mean the actual radon in the Las Vegas chamber.

In order to use figure 2 to calculate the “true” radon in the secondary chamber, find the elevation of the secondary chamber and determine the error of its cell calibration by using figure 2 and the correct curve (either a Pylon™ cell or a Rocky Mountain cell). Then subtract the error for the elevation of the primary calibration chamber. This difference is the net error that should be applied to the secondary chamber’s reported radon value.

As the first example, let us take a chamber in Colorado Springs, elevation 6000 feet using a Pylon™ cell. Reading from figure 2, we see the error is 0.078. Assuming that the chamber was calibrated by the U.S. EPA chamber in Las Vegas, we use figure 2 to find an error of about .03 for Las Vegas, which is at 2000 feet. Subtracting the Las Vegas error from the secondary chamber error, (0.078-0.030), we end up with a net error of 0.048. Thus, in order to find the “true” radon from the reported radon, using the original calibration factors, it is necessary to reduce the reported radon of the secondary chamber by .048, or 4.8 %. In other words, because Colorado Springs is at such a high elevation, it took about 5 % less radon to produce the same number of counts per second as the U.S. EPA used during its intercomparison with the Colorado Springs chamber. Also, any device which the Colorado Springs chamber exposes should use the chamber radon value reduced by about 5 %, assuming that the owner of the device wants to be calibrated or compared to the “true” radon value.

As a second example, let us take a chamber at sea level. Reading from figure 2, we see that error is 0 for the Pylon™ cell. Using the Las Vegas chamber for calibration gives us the .03 error again. Subtracting the Las Vegas error from the former, (0-.03), we get - .03 which means that the sea level chamber needs to raise its reported radon by about 3 % in order to reflect the “true” Las Vegas value. Failure to make these corrections among secondary chambers could result in an accumulated error as much as 7.8 % if, for example, a radon device is calibrated in a secondary chamber at sea level and is subsequently sent to a chamber at 6000 feet for an intercomparison. If, on the other hand, the Rocky Mountain cell was used in the initial calibration with the EPA chamber and the secondary chambers, the maximum error between chambers could, as seen in figure 2, be as high as 9.1 %.

Finally, for cells that have not been specifically studied, one can use a general theoretical predictive model introduced in an earlier paper (Burkhart, 2005). The graph, table 3, shows the maximum error between a chamber at sea level and a second chamber at 6000

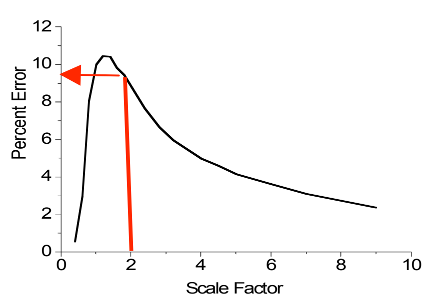

Table (3): This graph shows the predicted maximum error caused by using a cell that can be modeled as a Rocky Mountain cell scaled up to 9 times larger or down to 1/3 of its manufactured size. The arrows on the graph are used in a simple example that follows below which shows how to apply the graph to other cells.

feet. The Rocky Mountain cell is 9.7 cm in length and 7.0 cm in diameter. As an example, then, a cell which is two times as large, say, about 20 cm in length and 14 cm in diameter, would be expected to have a maximum error, from table 3, of around 9.5 %, distributed linearly from sea level to 6000 feet.

Comments

As was discussed in the above paper, it was necessary, for practical reasons, to experimentally calculate the error by counting each cell at one of the over-pressures and at ambient (6000 feet) and calculating the error by dividing by the ambient counts, i.e.,

$$\text{Error} = \frac{N_h - N_l}{N_h} \ . \qquad \text{(Equation 2)}$$

However, in order to compare with previous theoretical work, it was necessary to convert this equation to one in which the error was determined by dividing by N_l, i.e.:

$$\text{Error} = \frac{N_l - N_h}{N_l} \ . \qquad \text{(Equation 3)}$$

This was done by taking the error in each row of table 1, which is a fractional error compared to 6000 feet (ambient) and changing it to a fractional error compared to sea level:

Start with $$\text{Error} = \frac{N_h - N_l}{N_h} \ .$$

Subtract both sides from 1 and divide both sides by the error

$$(1 - \text{Error})/\text{Error} = (1 - \frac{N_h - N_l}{N_h})/\text{Error} \ .$$

Substituting the value for the error from equation 2 into the right hand side, we get:

$$(1 - \text{Error})/\text{Error} = (1 - \frac{N_h - N_l}{N_h})/(\frac{N_h - N_l}{N_h}) \ .$$

Taking the reciprocal of both sides and dividing through by the denominator on the right, we get:

$$\text{Error}/(1\text{-Error}) = 1/\ (1\ /(\frac{N_h - N_l}{N_h} - 1\ )),$$ which, after multiplying and dividing the right hand side by N_h-N_l gives:

$$\text{Error}/(1\text{-Error}) = (N_h - N_l)/(N_h - N_h - N_l)$$

And canceling the N_h's in the denominator and multiplying and dividing the right hand side by -1, gives:

$$\text{Error}/(1 - \text{Error}) = (N_l - N_h)/N_l,$$

which is equation 3, the definition of the error as measured from the lower elevation.

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