# Elevation Effects on Radon Cell Counting Efficiency

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## Abstract

Because of the change in path-length of the alpha particle as a function of air density, it has long been suspected that scintillation cells would have different counting efficiencies at different air densities (elevations), where counting efficiency is here defined as that fraction of radiation produced within the cell that is actually counted. However, except for a few isolated examples (George, 1983; Eberline, 1987), no literature has been found which examines this phenomenon in a general way. This paper presents a theoretical model which predicts this change in counting efficiency as a function of air density and cell geometry and reports on several attempts to quantify this change experimentally. Among the various cylindrical scintillation cells commonly available, it is predicted that the counting efficiency of scintillation cells at higher elevations (6000 feet (1969 m) or 820 millibar) increases (compared to lower elevations of 820 feet (266 m) or 990 millibar) as the size of the cell increases until a certain geometry is reached, peaking at around a 10 % increase for a cell with a diameter of approximately 7 cm and a length of approximately 9.7 cm. The counting efficiency at higher elevations (compared to lower elevations) then drops off for cells larger than this, apparently approaching a modest 1.3 % increase for cells ten times larger. Finally, it is suggested that these errors are sufficiently large enough so that they have to be corrected for under the current methodology used in inter-comparisons between commercial chambers and the U.S. EPA facility in Las Vegas.

## Introduction

One standard way to intercompare radon values is to sample the radon at one primary location, using an approved grab sampling method and a scintillation cell, and sending the cell to another, secondary, location for analysis. The second location, after analyzing the cell's contents, can then "correct" its own calibration factor for the cell/counting

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system and force its own counting system (by calculating a calibration factor) to report the same radon concentration as the primary location. In this way, both locations will report identical radon concentrations for this particular inter-comparison and, if nothing changes, for all future intercomparisons. By extension, many different locations can all intercompare with the primary location. This creates a network of secondary locations all "calibrated" to the primary location in which this initial location is therefore thought of as setting the standard. Indeed, this is the way in which several calibration and performance testing radon chambers are calibrated. The primary location, the standard setting location, is the U.S. EPA's Las Vegas facility. More specifically, the authors each run a radon chamber which is calibrated to the Las Vegas facility in exactly the manner outlined above.

This technique has proven very successful and results in the network of secondary locations being able to read the radon coming from the primary location to within a percent or two of the target value in subsequent intercomparisons.

There is a drawback, however. The resultant calibration factors that are forced onto the secondary locations are dependent upon the air density of the radon/air mixture within the cell. Since the cell is filled at one elevation (in this case, the 2205 feet (672 m), or 933 millibar) of Las Vegas), there may be errors when the cell is refilled at the home location (which could be at a lower or a higher elevation) when the cell is subsequently used to calibrate another instrument. This is because the alpha particles which strike the scintillation material have a path-length which is dependent upon the air density in the cell. To a good approximation, the path-length at sea level, in cm, can be written as:

$$R = 0.32\ E^{3/2} \qquad \text{(Equation 1)}$$

where E is the initial energy (in MeV) of the various alpha particles from radon-222, polonium-218 and polonium-214. For Dayton, Ohio, the ranges of the alphas would be:

Radon-222; 4.12 cm
Polonium-218; 4.70 cm
Polonium-214; 6.70 cm.

The range increases as the air density, $\rho$, decreases:

$$R_l\ \rho_l = R_h\ \rho_h \qquad \text{(Equation 2)}$$

where the subscript l describes low elevations and the subscript h, high elevations, so that in Colorado Springs, the ranges of the alpha particles become:

Radon-222; 4.99 cm
Polonium-218; 5.70 cm
Polonium-214; 8.13 cm.

Clearly, for a given radon concentration, a cell filled at a higher elevation will have more alpha particles strike the interior cell walls than will a cell filled at lower elevations, especially when the diameter or length of the cell is in the neighborhood of the path length of the alpha particles at the higher elevation. This increases the counting efficiency (cpm/dpm) of the cell at higher elevations as the cells record more counts (cpm) for a given radon concentration. Conversely, the counting efficiency is lower at lower elevations. Consequently, using the cell at its new location, where the elevation is higher or lower than the primary calibration facility, results in an error in the calculation of the radon concentration that we have found to be as great as 9.8 % for the particular cell (with a volume of approximately 0.37 liters) which is preferred by the U.S. EPA and has become, in essence, the standard cell used in the industry. Other commonly used cells, with greater or lesser volume, tend to have a smaller difference in counting efficiency.

**The Calibration Procedure**

The left-most portion of the block diagram, given in figure 1, shows how the cells are originally calibrated. For clarity, radon values are shown using three units simultaneously. The first unit is decays per second (dps). This is the actual number of radon/radon decay product atoms decaying within the cell each second. The second unit is counts per second (cps). This is the number of alpha particles being counted by the cell each second. This number, of course, is dependent upon the fraction of alpha particles that are being produced which actually strike the cell interior surface and produce a light emission. The third unit is the commonly-used unit, picocuries per liter, which gives the radon concentration. The actual numbers being used here are fictitious and are for demonstration purposes only.

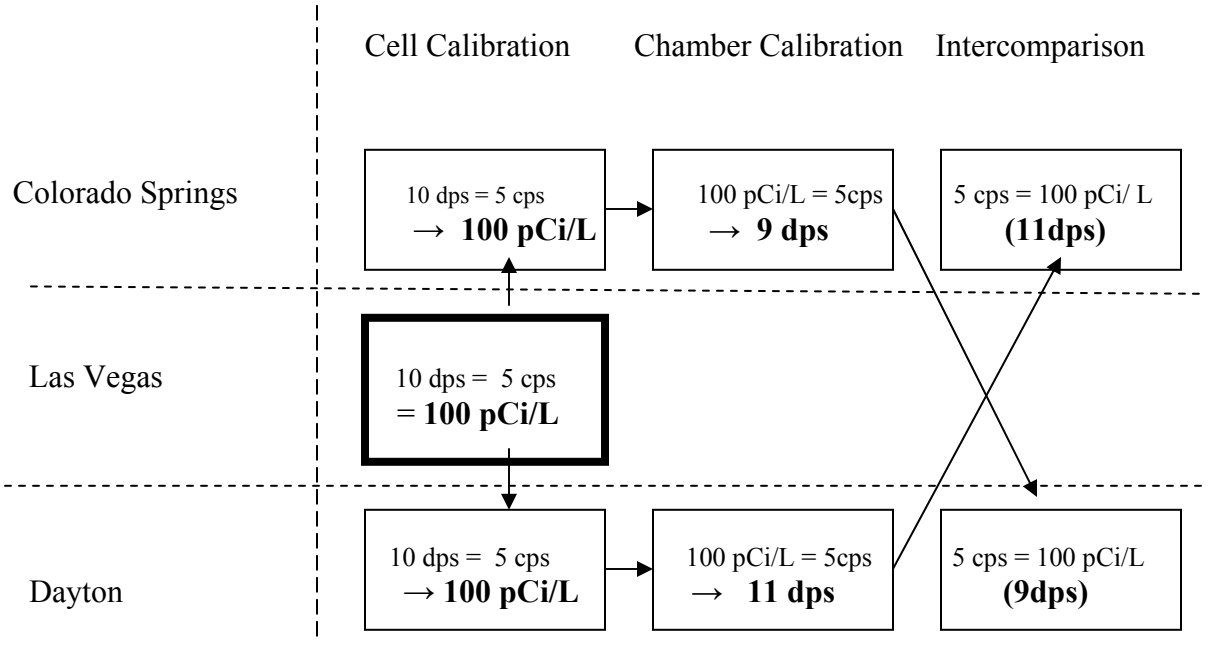


Figure (1): A block diagram showing calibration of cells stage (left), subsequent calibration of chambers from the cells (middle) and, lastly, intercomparison of radon in the chamber using cells filled at each site.

During the calibration phase, two identical cells are filled with radon at Las Vegas. Las Vegas has determined that the radon in the cells is, say, 100 pCi/L and, for the purposes of this diagram, it is assumed that this concentration of radon corresponds to 10 dps and, at the elevation of Las Vegas, an actual count of 5 cps. These sealed cells are then sent to Dayton and Colorado Springs. This allows these two secondary facilities to calibrate the cells to 100 pCi/L whenever the cells read 5 cps (ignoring the exponential decay of radon and radon decay products and assuming identical counting equipment). It is important to notice that the cells at the two secondary locations both have 10 dps only because they were both filled at the Las Vegas elevation. However, the number of decays per second is not used in the calibration because only the counts per second are actually measurable.

In the center portion of the block diagram, the two secondary facilities calibrate their own chambers. A chamber is set to a particular radon value and a radon grab sample is taken out of the chamber. Each facility, using the calibration factors determined in the paragraph above, determines its chamber radon concentration is 100 pCi/L whenever it reads 5 cps from its cell, since that is what the two chambers had forced onto their counting systems. However, because the chambers are at different elevations and each cell contains a different air density, the actual decays per second which produce a 5 cps reading will be different. In this example, Colorado Springs, which is at a higher elevation, requires only 9 dps to produce 5 cps while Dayton, at a lower elevation, requires 11 dps to produce 5 cps because the alpha particles are attenuated by the more dense air inside the cell.

On the right-hand side of the block diagram, the chambers exchange radon in order to verify that they are each still calibrated to each other, and, by extension, Las Vegas. Colorado Springs fills a sealed cell at its elevation and sends the cell to Dayton. Dayton does the same and sends its cell to Colorado Springs. Since each secondary facility is calibrated so that 5 cps equals 100 pCi/L of radon, each facility will report that the other is at 100 pCi/L even though the actual decays per second are different in each cell.

**When Does the Error Show Up?**

In reality, of course, the two chambers do not have identical radon concentrations. The Colorado Springs facility has only enough radon to produce 9 dps while the Dayton facility is outputting 11 dps. So, the Colorado Springs chamber is, in actuality, at a radon concentration less than 100 pCi/L, say 95 pCi/L, while the Dayton facility is greater than 100 pCi/L, say 105 pCi/L. Comparing the two chambers to Las Vegas or to each other, as demonstrated in the above paragraph, by exchanging cells will not uncover this discrepancy. However, every tertiary user who subsequently calibrates to Colorado Springs will slightly over-report the radon concentration when using their device in a client's house since 9 dps (once converted to counts per second by their instrument) will be reported as 100 pCi/L. Tertiary users who calibrate to Dayton will slightly under-report the radon when using their device in a client's house as it will take as many as 11 dps (once converted to counts per second by their instrument) to report 100 pCi/L. Finally, users who calibrate at Dayton and then send their device to the Colorado Springs

chamber (for spiking or a performance test) will under-report the Colorado Springs chamber radon value. Conversely, tertiary companies who calibrate at Colorado Springs and then send their device to Dayton for spiking or a performance test will slightly over-report the Dayton radon value.

**A Theoretical Model**

Quite simply, a scintillation cell works by emitting visible light each time an alpha particle strikes the scintillation material (which in this case is zinc sulfide). Any radon decay products that may be present in the air which is being sampled are filtered out and prevented from entering the cell. Thus, the cell initially contains an air/radon mixture. It is assumed that the radon is uniformly distributed throughout the cell, there being no preferred location for the radon to congregate and no plating of the radon onto the cell's interior surfaces. It is further assumed that secular equilibrium has been reached and that the two polonium species are uniformly distributed on the interior surface of the cell.

All of the cells modeled for this paper are cylindrical in shape, completely air tight and have a window on one end. Except for the window, the rest of the interior of the cell is considered to be covered in scintillation material. See figure 2.

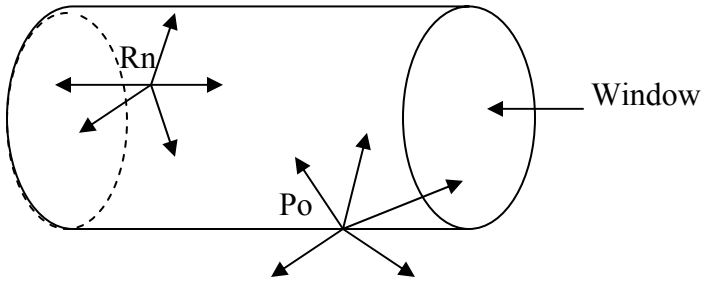


Figure (2): A typical cylindrical cell used for grab sampling. A glass window on the right is not covered with scintillation material. For simplicity, the fittings used to fill the cell are not shown. A typical radon-222 atom is shown within the air inside the cell. The arrows represent possible paths for the alpha particle released by the radon. A typical polonium-218 or polonium-214 atom is shown plated out on the bottom right of the interior of the cell. Theoretical paths for its alpha are also shown with arrows. Of course, alpha particles can not penetrate the walls of the cell and such paths would be counted as hits, or flashes.

Since secular equilibrium has been reached, each of the three sources is producing the same number of alpha particles per unit time. To consider the total number of alpha particles counted, we place point sources at all places along the walls and within the air inside the cell. For each point source, probable paths for the alpha particles are found by assuming a spherically uniform distribution of such paths. The alpha particles are allowed to travel their maximum range (which depends, of course, upon the density of air within the cell). We then calculate whether a given alpha particle has hit the side wall of the cylinder or the left hand side of the cylinder and has created a light flash. The window is not covered with ZnS and therefore does not contribute to the number of flashes produced (even though radon decay products are assumed to plate out on the window). We then numerically sum over all the source points, either in the air or along the walls and see

how many of the emitted alpha particles hit the ZnS and caused a flash of light. For the same geometry and sized cell, the calculation is repeated for a different elevation (air density). Then, the percent difference in cell counting efficiency can be found as a ratio of the number of alpha particles that are counted at the two different elevations using the following equation:

$$\text{Percent difference} = \frac{N_h - N_l}{N_l} \times 100 \qquad \text{(Equation 3)}$$

Where $N_h$ is the number of alpha particles counted at high elevation and $N_l$ is the number counted at low elevation. Since this gives a ratio of alpha particles counted (when both cells have the same number of alpha particle sources), this is equivalent to comparing the percent difference in cell counting efficiencies.

**The Experimental Methodology**

The authors, after much discussion, concluded that the most straightforward way in which to verify this difference in cell counting efficiency would be to compare the radon results at the two locations using the same set of cells. However, it had already been established that the difference would not be seen by simply filling cells and sending them to the other location because the cells are sealed and the air pressure (and the cell counting efficiency) is preserved even when measured at the other location.

In order to avoid these complications, a Tedlar® bag would be filled with radon at one location. Two cells would then be filled from the Tedlar® bag at that same location. The time of filling and the air pressure (in millibar) was recorded. The Tedlar® bag, still containing radon, and the two filled cells were then sent to the second location. The two cells were then read at the second location. This radon concentration was recorded. Then, the cells were cleaned and reloaded with radon from the same Tedlar® bag. The bag was, of course, at a different pressure than it was when the cells were filled originally and the bag had either expanded or contracted between the fills. The cells, now filled at a different pressure were read and the radon recorded. This second radon value was then adjusted for the difference in radon concentration caused because the radon source (the bag) had expanded or contracted between cell fills. This correction simply multiplies the measured radon concentration by the ratio of the pressures at the two locations. In other words, the radon concentration within the bag, in picocuries per liter, is 20 % greater in Dayton than it is in Colorado Springs because the bag is compressed by 20 % by the greater atmospheric air pressure in Dayton.

Finally, the two radon values, the radon measured in the cells filled at the first location and the radon measured in the cells filled at the second location (corrected for pressure differences and for the passage of time) are compared. Since those cells which were filled at the Colorado Springs location were expected to have a higher counting efficiency, it was expected that the two radon values would not be the same. It was anticipated that the cells filled in Colorado Springs would show a slightly higher radon value than the cells

filled at Dayton even though both cells were filled from the same radon in the same Tedlar® bag because a greater percentage of alpha particles would strike the ZnS at the lower air pressure of Colorado Springs.

**Theoretical Results**

The theoretical results derived from the math model were very clear. Three different scenarios were run. In the first scenario, the actual geometries and sizes of commonly used cells were entered and the percent difference in cell counting efficiency was determined. In the second scenario, only one particular cell was modeled, the Rocky Mountain cell. This time, the theoretical error caused by counting efficiency was calculated for the two different elevations of Dayton and Las Vegas and again for Las Vegas and Colorado Springs. In the third scenario, only one cell was modeled. However, the cell was run for many different sizes (scaled up and down) in order to see if there was any particular size (scale) for this cell which had the greatest "error" caused by a difference in cell counting efficiency at different elevations. Here are the results:

First scenario: Four commonly used cells are "filled" at Dayton Ohio. The radon is measured. The four cells are "filled" again at Colorado Springs (with the exact same radon and radon decay product activity, corrected for pressure differences) and measured again. The "error" is calculated, where the error is defined as the percent difference found by equation 3.

| 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 % |
| Custom Made | 20 cm | 27.5 cm | 6.1 % |

These theoretical results are especially interesting because the cell that is used by the EPA and the two secondary chambers is the Rocky Mountain cell, the one with the greatest error.

In the second scenario, we attempted to break down the 9.8 % difference in counting efficiency and divide it into two pieces: how different is Dayton from Las Vegas and, then, how different is Colorado Springs from Las Vegas? Although Las Vegas has an intermediate elevation (2205 feet) between Dayton (820 feet) and Colorado Springs (6000 feet), is was anticipated that the percent difference would be smaller between Dayton and Las Vegas because the elevation difference is also smaller. When the model was actually run, the percent difference was indeed smaller between Dayton and Las Vegas for the Rocky Mountain cell, with an "error" of 3.4 % and an "error" of 6.2 % between Las Vegas and Colorado Springs, where the percent difference each time was calculated by dividing by the number of light flashes, $N_l$, at the lower elevation as in equation (3).

Third scenario: The Rocky Mountain cell geometry is used repeatedly. However, each time the program is run, the cell size changes (either larger or smaller). With each size cell, the cell is "filled" at Dayton Ohio and again at Colorado Springs, as in the example above and the "error" calculated. In figure 3, the results are shown graphically

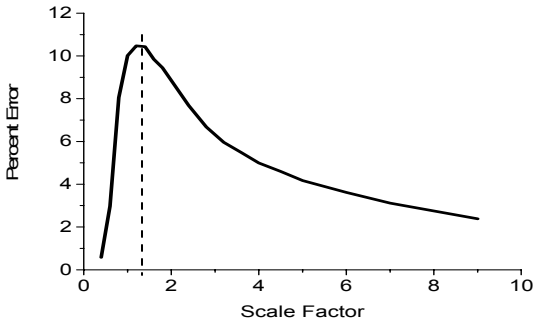


Figure (3): Percent error versus scale factor the Rocky Mountain cell geometry. The scale factor gives the increase or decrease in both the height and diameter from the original cell geometry.

Notice that the error for the Rocky Mountain cell geometry peaks at around 10 % for a scale factor of 1.3. For cells of a smaller size, the path length of the alpha particles is sufficient to allow all the alpha particles to strike the cell walls and emit a flash. Hence, for small cells, the counting efficiency is not much affected by path length changes. For cells larger than a scale factor of 1.3, the path length of the alpha particles is not sufficiently long to allow the alpha particles to cross over from one cell wall to the opposite wall (or, for most alpha particles, the end wall) so that path length again becomes less of an issue at lower air densities (higher elevations).

**Experimental Results**

As explained in the experimental methodology section above, it proved necessary to measure the "same" radon at the two different elevations, where a volume correction had to be made on one of the radon values because a flexible bag was used to transport the radon between locations and the bag volume changes as a result of atmospheric pressure differences. Only the Rocky Mountain cells were used for the experiment because of time constraints and because, for practical purposes, it is the Rocky Mountain cell which is used for the initial calibration with the U.S. EPA and for inter-comparisons between the two chambers. Shown in tabular form, therefore, is $C_h$, the radon measured at Colorado Springs and $C_l$, the radon measured at Dayton Ohio, after normalization for atmospheric pressure differences. Finally, the "error" is calculated using equation (1) with radon values replacing number values:

$$\text{Percent difference} = \frac{C_h - C_l}{C_l} \times 100 \qquad \text{(Equation 4)}$$

| Date | $C_l$ | Dayton Air Pressure | $C_h$ | Colorado Air Pressure | Percent "Error" |
|---|---|---|---|---|---|
| 9/8* | 228 pCi/L | 991 mb | 263 pCi/L | 819 mb | 15.7 % |
| 9/8* | 226 pCi/L | 991 mb | 261 pCi/L | 819 mb | 15.7 % |
| 8/5* | 411 pCi/L | 993 mb | 452 pCi/L | 820 mb | 10.1 % |
| 8/5* | 408 pCi/L | 993 mb | 444 pCi/L | 820 mb | 8.8 % |
| 7/19 | 568 pCi/L | 985 mb | 578 pCi/L | 818 mb | 1.8 % |
| 7/19 | 513 pCi/L | 985 mb | 580 pCi/L | 818 mb | 13.1 % |
| 6/30 | 117 pCi/L | 988 mb | 130 pCi/L | 818 mb | 11.1 % |
| 6/30 | 122 pCi/L | 988 mb | 129 pCi/L | 818 mb | 5.7 % |

* Dates marked with an asterisk indicate when the cells were being read at Dayton. All other cells were read at Colorado Springs.

The last column on the right indicates that there is an experimental difference in cell counting efficiency between Dayton and Colorado Springs. The average "error", that is the average percent difference in cell counting efficiency is 10.2 % with a one sigma of 4.8 %. The 10.2 % average error is in reasonably good agreement with the theoretically predicted 9.8 % and is close to the 9 % error suggested by the two references.

**Summary**

We have presented both a theoretical model and experimental evidence that there is a measurable difference in cell counting efficiency when cylindrical scintillation cells are used to measure radon concentrations at different elevations. The counting efficiency (cpm/dpm) is affected because there are different path lengths for the alpha particles within the cell at different elevations. Although this difference has been long suspected, there has not been any general discussion (theoretical or experimental) until now. In particular, this paper has looked at four different commonly used cells and has examined, in detail, one of the more popular cells. We suggest that the Rocky Mountain cell, which is currently used by the U.S. EPA and the two performance test chambers in the U.S. has the greatest potential "error" in that using the cell at different elevations results in the largest percentage difference in cell counting efficiency. Since the "error" is in the neighborhood of 9.8 % between the two locations studied, and since both locations are used for performance testing and to calibrate other instruments, it is recommended that modifications be made to the appropriate protocols to correct for this phenomenon.

**References**

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