American Association of Radon Scientists and Technologists 2007 Proceedings
of the 2007 AARST International Symposium Jacksonville, FL, 2008©AARST

USING CONTINUOUS MONITORS TO TEST THE UNIFORMITY OF A RADON CHAMBER

Phillip H. Jenkins, PhD, CHP
Bowser-Morner, Inc., Dayton, Ohio

ABSTRACT

The radon chamber at Bowser-Morner was designed to ensure that the concentration of radon throughout the chamber is uniform. Nevertheless, it is important to demonstrate this uniformity periodically with measurements. To that end, 36 continuous radon monitors were simultaneously deployed in the chamber in a statistically balanced pattern and were exposed for a period of 48 hours. The resulting measurements of average radon concentration were analyzed using a two-way analysis of variance (ANOVA). The results showed that any nonuniformity was not statistically significant. The radon monitors averaged 25.6 pCi/liter with a coefficient of variation (COV) of 3.4%. Other sources of uncertainty that contribute to the COV are discussed, such as the "counting statistics" during the 48-hour exposure in the chamber and the calibration process. These considerations support the conclusion that if there is nonuniformity of radon concentration in the chamber, it is so slight as to be difficult to detect.

INTRODUCTION

The radon (in this paper "radon" means radon-222 only, not including its decay products) chamber at Bowser-Morner, Inc. (BMI) was designed to have a floor plan and air-flow pattern essentially identical to those of the Environmental Protection Agency's (EPA's) radon chamber at the Radiation and Indoor Environments Laboratory (RIEL) in Las Vegas. The inside dimensions of the BMI chamber are 3.7 m x 3.7 m x 2.7 m (12 ft x 12 ft x 9 ft). Air is circulated between this chamber and a 0.2-m^3 (8-ft^3) external environmental conditioning chamber at a rate of 2.8 m^3 min^{-1} (100 ft^3 min^{-1}) forming nearly a closed loop. The velocity of air in the chamber is 3 to 6 m min^{-1} (10 to 20 ft min^{-1}), similar to the velocity measured by the author in the large radon chambers formerly at the EPA's radon laboratory at the Eastern Environmental Radiological Facility (EERF) in Montgomery, AL.

The design of continuous air flow between the large radon chamber and the smaller environmental chamber helps to ensure that the concentration of radon is uniform throughout the portion of the radon chamber that is used for exposure of devices. This is important as it is essential that devices placed in the chamber for exposures to radon are subjected to the same concentration regardless of the location in the chamber. With the size of the BMI chamber and the flow rate through it, the mean residence time of the air in the chamber is 13 minutes. The

loss of radon from the air due to decay during transit through the chamber is less than 0.2%. In order to keep the radon concentration in the chamber relatively constant, radon that is lost to decay, and possibly some leakage, is replaced by continuously injecting radon from a flow-through radium-226 source into the environmental conditioning chamber. Because the volume of the conditioning chamber is small compared to the radon chamber, the radon concentration in the conditioning chamber and in the inlet to the radon chamber must be slightly larger than the concentration in the radon chamber in order to replenish the lost radon. This creates some concern that there could be a higher radon concentration in the portion of the radon chamber near the entry than exists in the rest of the chamber. The manner in which the inlet flow enters the chamber is designed such that there is considerable mixing near the ceiling before the incoming air and radon reach the shelf units where devices are exposed. However, it is important to verify periodically that the radon concentration is truly uniform throughout the portion of the chamber where devices are exposed by performing a uniformity study such as is the subject here.

The BMI chamber contains seven shelf units, identified as A through F, as shown in Figure 1. Each shelf has dimensions of 0.6 m x 1.2 m (23.5 in x 46 in). Shelf unit D contains two shelves and is used only for storage and a work space; therefore, devices are not exposed on shelf unit D, and it is not considered further here. The remaining six shelf units each contain five shelves, labeled 1 through 5, as shown in Figure 2. The shelves are spaced 0.4 m (14.5 in), 0.8 m (31 in), 1.3 m (53 in), 1.6 m (64 in) and 1.9 m (75 in) from the floor.

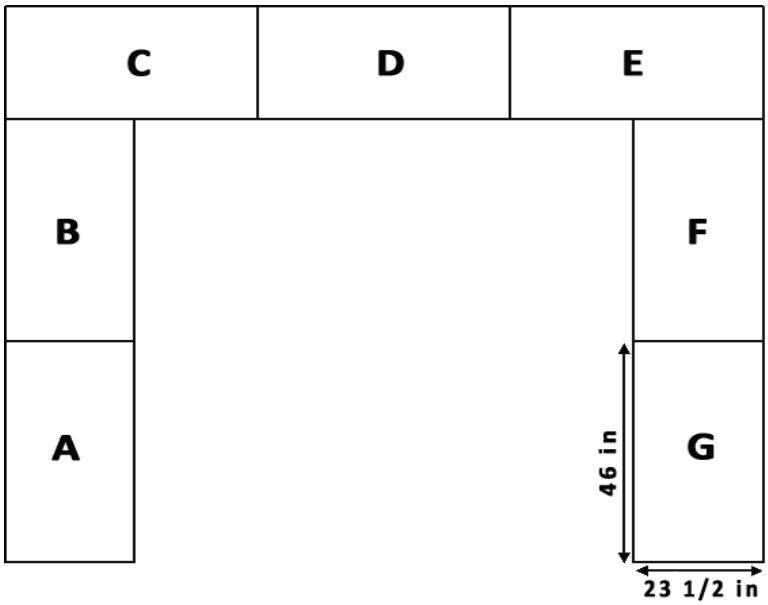

Figure 1. Layout of shelf units inside BMI chamber.

This chamber uniformity study can be thought of as analogous to measuring the radon concentration throughout a building, with each level of shelves analogous to floors in a building and the individual shelves at each level analogous to rooms on a given floor of the building. If one were faced with mapping the radon concentration throughout a building, the same type of statistical considerations for the design of the study described here would apply.

With the cooperation of personnel from femto-TECH, Inc., the author was able to borrow a number of recently calibrated continuous radon monitors, Model CRM510, for a weekend for this study. Because it is desired to test statistically any nonuniformity among the individual shelves in the chamber, it is necessary to place more than one monitor on each shelf involved in the test. The reason for this is made clear in the discussion below. It would have been ideal to place two monitors on each of the thirty shelves that are used in the chamber for exposure of devices, thus involving all of the shelves in this study; however, sixty continuous monitors were not available at that time. A good compromise design for the study was to consider only shelf levels 1, 3 and 5, requiring 36 monitors. This approach ensures that the concentration is measured from the top shelf to the bottom shelf on each unit, with the third level (level 3) being between the top and bottom shelves, thus covering the entire volume in which devices are exposed in the chamber.

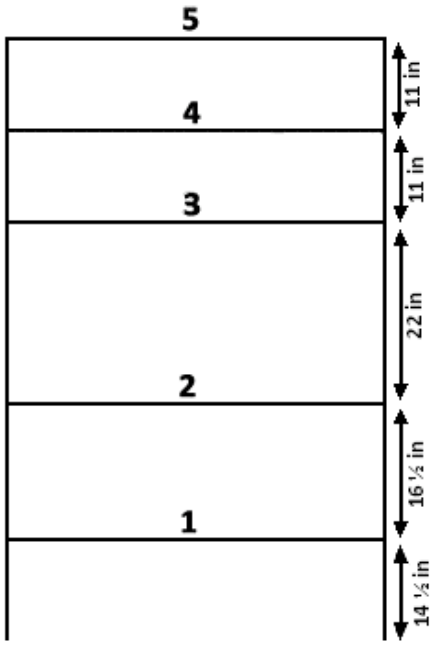

Figure 2. Shelves in each shelf unit in BMI chamber.

DESIGN OF THE EXPERIMENT AND STATISTICAL MODEL

The design of the experiment described above is called a Completely Randomized Design (CRD). Descriptions of such a design can be found in numerous statistical texts (such as Ostle 1963). The sources of variation that are to be tested are the shelf level (L_i), the shelf unit (U_j) and the individual shelves, which statistically are represented by the interaction between L_i and U_j, (LU_{ij}). The measurements are replicated by placing two monitors on each of the eighteen shelves being considered, thus providing a basis for performing a statistical test on a possible effect due to the individual shelves. An underlying assumption here is that the concentration is uniform on any given shelf and thus the two monitors placed on any shelf are subjected to radon at the same concentration. The model for this design is as follows:

$$Y_{ijk} = \mu + L_i + U_j + LU_{ij} + \varepsilon_{ijk} \quad (1)$$

where Y_{ijk} = the individual measurements (36 degrees of freedom)
μ = the effect of the mean of the measurements (1 degree of freedom)
L_i = the effect of the ith shelf level (2 degrees of freedom)
U_j = the effect of the jth shelf unit (5 degrees of freedom)
LU_{ij} = the effect of the interaction between L and U; i.e. the effect of the ijth shelf (10 degrees of freedom)
ε_{ijk} = the error term; i.e., the effect of the individual monitors (18 degrees of freedom)

Note that there is one degree of freedom (df) for each monitor in the study. The effect due to the mean of the measurements (μ) takes one degree of freedom. The number of degrees of freedom for the effect due to shelf level is the number of levels minus one, i.e. 2 df. Likewise the number of degrees of freedom for the effect due to the shelf units is the number of units minus one; i.e., 5 df. The number of degrees of freedom for the effect due to the interaction, LU_{ij} (the individual shelves) is 2 x 5 = 10 df. The number of degrees of freedom for the error term, which in this case is the effect of the individual monitors, is the number of monitors on each shelf (2) minus one times the number of shelves, i.e. 18 df. Note that if there was only one monitor on each shelf, there would be no df for this term and no basis for a test for an effect due to the individual shelves. In other words, the effect of the variation among the monitors themselves would be confounded with any possible effect due to the individual shelves, and there would be no way to differentiate between these two sources of variation. This is the reason why it was necessary to place more than one monitor on each shelf.

It is possible to design an experiment where not every shelf is replicated; in other words, there is only one monitor on each of some of the shelves. With such a design it would have been possible to cover more of the shelves, including some or all shelves at levels 2 and 4 in addition

to levels 1, 3 and 5. However, the design and analysis would be more complicated. The design used here is adequate and much simpler to analyze. A full discussion of a more complicated experimental design is beyond the scope of this paper.

METHOD

On Friday morning, January 26, 2007, BMI and femto-TECH personnel placed the 36 monitors on the shelves as shown in Figure 3. The monitors were allowed to equilibrate with their environs for at least four hours and were started at roughly 3:00 pm. The monitors ran for 48 hours, with the run ending on Sunday afternoon. On Monday morning, the same personnel retrieved the monitors from the chamber and printed their measurements.

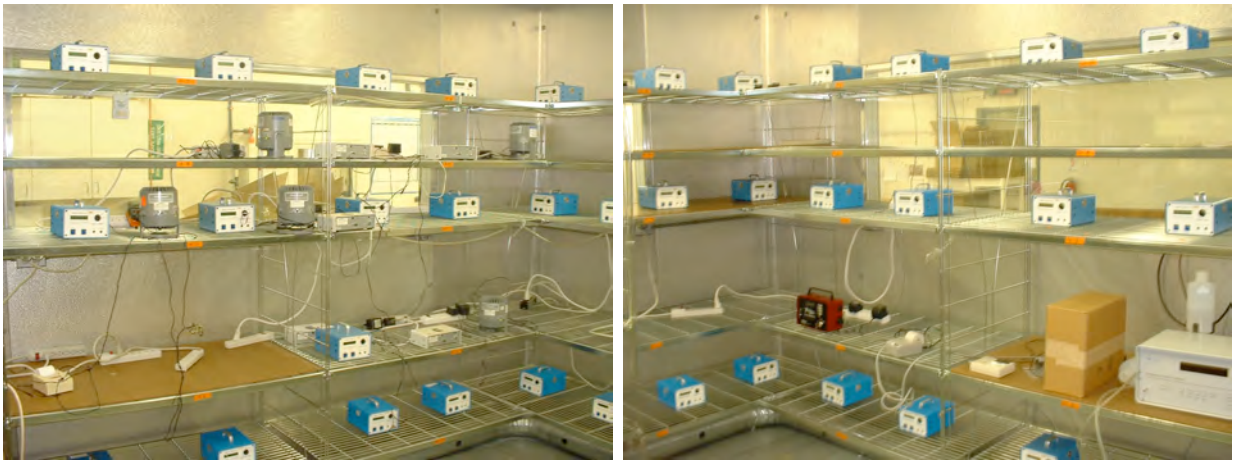

Figure 3. Placement of monitors on Shelf Units A, B & C (left) and Shelf Units E, F & G (right) for chamber uniformity study. Other monitors are present for calibration or other quality assurance purposes.

RESULTS

The results from the measurements from the monitors are shown in Table 1. From inspection of the results there is no obvious trend in the measurements, but a statistical analysis is required to be certain. Table 2 shows the average and standard deviation of each pair of results for each of the eighteen shelves tested. Again, from inspection there is no obvious trend. The averages ranged from 24.9 pCi/liter to 26.7 pCi/liter and the standard deviations ranged from 0.1 to 2.1 pCi/liter. The fact that some of the standard deviations of the averages of the pairs of results were greater than the spread of the average measurement values (1.8 pCi/liter) is a strong hint that no trend can be seen among the shelf units, shelf levels or individual shelves; however, a proper statistical analysis is still required.

In Table 3, the average and standard deviation of the twelve measurements for each shelf level are shown in the right-most column, and the average and standard deviation of the six measurements for each shelf unit are shown in the bottom row. The average and standard deviation of all thirty-six measurements are shown at the bottom of the right-most column.

Note that there is a hint of a trend in the averages of the shelf levels, with the averages of levels 1, 3 and 5 being 25.8, 25.5 and 25.4 pCi/liter; however, not only is this possible trend the opposite of what might be expected considering that level 5 is nearest the inlet to the chamber, but also the variation here is well within the standard deviations of the averages. The average concentration values for the six shelf units ranged from 25.3 to 26.2 pCi/liter, a spread of 0.9 pCi/liter. However, the standard deviation values for the shelf units ranged from 0.7 to 1.4 pCi/liter, indicating that any differences among the shelf units are not significant. These indications are apparent by inspection of Table 3, but do not constitute a statistical evaluation.

	Shelf Units					
	A	**B**	**C**	**E**	**F**	**G**
Shelf Number **5**	**26.2** **24.2**	**25.9** **23.9**	**25.9** **26.0**	**24.9** **25.1**	**26.2** **25.6**	**26.3** **24.8**
3	**25.8** **25.6**	**24.7** **26.7**	**27.4** **24.6**	**25.6** **25.0**	**24.9** **25.2**	**25.5** **25.1**
1	**25.7** **26.1**	**24.5** **27.4**	**26.3** **27.0**	**26.5** **24.9**	**24.3** **25.7**	**24.9** **26.2**

Table 1. Measurements in pCi/liter of the 36 monitors used in the study.

One might think that it would be appropriate to use a series of t-tests to test for significant differences among the shelf levels, shelf units or individual shelves. For example, a t-test could be used to test the average and standard deviation of the measurements made on unit A to those of unit B, unit A to unit C, etc. until all combinations of two shelf units have been tested. In a similar manner the shelf levels and even the eighteen individual shelves could be tested. However, for reasons beyond the scope of this paper, this procedure is not valid. Rather, the

proper statistical analysis procedure is Two-Way Analysis of Variance (ANOVA). The ANOVA calculations can be found in standard statistical texts (such as Ostle, 1963, pp. 318 – 321) and in various statistical software products; but the calculations are easily performed using functions existing within Microsoft Excel. Table 4 contains the ANOVA table resulting from analyzing the data in Table 1 using the ANOVA procedure in Microsoft Excel.

Shelf Level	Shelf Units A	B	C	E	F	G
5	25.2 ± 1.4	24.9 ± 1.4	26.0 ± 0.1	25.0 ± 0.1	25.9 ± 0.4	25.6 ± 1.1
3	25.7 ± 0.1	25.7 ± 1.4	26.0 ± 2.0	25.3 ± 0.4	25.1 ± 0.2	25.3 ± 0.3
1	25.9 ± 0.3	26.0 ± 2.1	26.7 ± 0.5	25.7 ± 1.1	25.0 ± 1.0	25.6 ± 0.9

Table 2. Averages and standard deviations of the two measurements on each of the eighteen shelves.

	Shelf Units A	B	C	E	F	G	Avg ±

Shelf Level							
5	25.2 ± 1.4	24.9 ± 1.4	26.0 ± 0.1	25.0 ± 0.1	25.9 ± 0.4	25.6 ± 1.1	25.4 ± 0.8
3	25.7 ± 0.1	25.7 ± 1.4	26.0 ± 2.0	25.3 ± 0.4	25.1 ± 0.2	25.3 ± 0.3	25.5 ± 0.8
1	25.9 ± 0.3	26.0 ± 2.1	26.7 ± 0.5	25.7 ± 1.1	25.0 ± 1.0	25.6 ± 0.9	25.8 ± 1.0
Avg ± s	25.6 ± 0.7	25.5 ± 1.4	26.2 ± 1.0	25.3 ± 0.6	25.3 ± 0.7	25.5 ± 0.7	25.6 ± 0.9

Table 3. Averages and standard deviations by shelf, shelf unit, shelf level and overall.

ANOVA					
Source of Variation	**SS**	**df**	**MS**	**F**	**F_{crit}**
Shelf Level	**0.917**	**2**	**0.459**	**0.430**	**3.55**
Shelf Unit	**3.189**	**5**	**0.638**	**0.598**	**2.77**
Interaction (Shelf)	**3.016**	**10**	**0.302**	**0.283**	**2.41**
Within	**19.21**	**18**	**1.067**		
Total (corrected)	**26.33**	**35**			

Table 4. Analysis of Variance (ANOVA) table for the CRD.

DISCUSSION

A complete discussion of ANOVA is beyond the scope of this paper; however, some discussion of the results shown in Table 4 is necessary. The first column contains the sources of variation: Shelf Level, Shelf Unit, the interaction between those two sources (the individual shelves), the "within" variation and the total variation. The "total" has been corrected for the effect of the mean, so one degree of freedom has been lost to the mean, leaving 35 degrees of freedom (the total number of monitors minus one) for the total. The "within" variation is that caused by differences between the two monitors on each of the eighteen shelves. The next column is the sum of squares (SS). This is a measure of the variation due to each of the sources. Each value of SS is divided by its associated number of degrees of freedom (df) to obtain the mean square (MS). The Within MS forms the basis for testing the significance of the other sources of variation. This is done by dividing the MS for each of the other sources of variation by the Within MS to obtain the value of the F-statistic. The F statistic is the ratio of two measurements of variance. The value of the F-statistic for the Interaction (individual shelves), which is 0.283, was obtained by dividing the Interaction MS by the Within MS. Likewise, the values of the F-statistic for Shelf Unit and Shelf Level were calculated to be 0.598 and 0.430, respectively.

The values of the F-statistic are used to test the hypotheses that each of the sources of variation is zero; i.e., that there is no effect from that source. The critical values of F are shown in the last column of Table 4. If the F-value for any of the sources of variation was greater than the corresponding critical value, then the hypothesis that the effect of that source of variation is zero would be rejected at the 95% confidence level ($\alpha = 0.05$). In this case, because none of the F-values is greater than the critical value, the hypotheses that the effects of these sources of variation were zero cannot be rejected. In fact, the values of the F-statistics are so small that one can accept the null hypotheses; in other words, accept that there are no significant effects due to the sources of variation tested.

Normally, one would expect the values of the F-statistic to be greater than one. In fact, statistics texts caution the researcher when values of the F-statistic less than one are found, as was the case here, because that may be an indication that there was something wrong with the experiment or the model being considered. In this case, however, these results appear to indicate that the variation among the measurements from the monitors is significant in comparison with the variation of the radon concentration throughout the chamber. In other words, in spite of the fact that the variation among the monitors was quite small, no variation among the shelf levels, shelf units or the shelves themselves could be observed. If there is variation in the radon concentration within the BMI radon chamber, then in order to measure that variation the devices used to measure the radon concentration in various locations in the chamber must have an even smaller variation amongst themselves.

It is important to understand what sources of uncertainty contributed to the variation among the monitors observed here in order to determine how that variation might be reduced in a future study such as this. The best measure of the variation is the Coefficient of Variation (COV). The COV is calculated by dividing the standard deviation of the 36 values shown Table 1 by the average of the values and multiplying by 100 to express the result as a percentage of the average. The average and standard deviation are shown in the lower, right-most cell in Table 3 as 25.6 and 0.9 pCi/liter, respectively. The standard deviation of the 36 measurements can also easily be found by dividing the Total (corrected) SS value from Table 4 by the associated number of degrees of freedom (35) and taking the square root of the result. Regardless of the method used to obtain the value of the standard deviation, the COV is found to be 3.4%.

Assuming that there is no, or only trivial, variation of radon concentration in the BMI chamber, then the variation among the monitors observed here has to caused by other sources of variation. One source is the uncertainty in the counting of alpha pulses during the 48 hours of the chamber exposure for this study. The theoretical standard deviation and COV can be estimated by assuming that "counting statistics" apply. This means that the standard deviation of the net sample count rate can be estimated using the following equation:

$$s = [G/t_s + B/t_b]^{1/2} \quad (2)$$

where s = standard deviation of the net sample count rate (counts per min or cpm)
G = gross sample count rate (cpm)
t_s = sample counting time (min)
B = background count rate (cpm)
t_b = background counting time (cpm)

The net count rate, N (cpm) is:

$$N = G - B \quad (3)$$

and the COV is

$$COV = s/N \times 100 \quad (4)$$

The theoretical COV values for all 36 measurements from this study were calculated in this manner and were found to average 0.7%. So, this source of variation is not a large contributor to the total observed (3.4%). This also indicates that using another device with greater sensitivity (i.e., a larger calibration factor in terms of cpm/pCi/liter) would not improve the variability among the monitors significantly. In a similar manner, the theoretical COV's for the 36

monitors due to counting statistics during their calibrations by the manufacturer were calculated using data provided by the manufacturer. The theoretical COV values from this source of variability averaged about 1.4%. When this 1.4% is propagated with the 0.7% from the chamber uniformity study, by taking the square root of the sums of squares of these two components (i.e., $[1.4^2 + 0.7^2]^{½}$), the result is only 1.6%. Therefore, a large portion of the variation among the monitors is unexplained by these sources of variation.

Another probable source of variation among the monitors is due to the fact that they were not all calibrated at the same time (i.e., were not in a radon chamber together during calibration). It is expected that there would be some variability between one calibration process and another, even if they are performed at the same facility by the same people. In an effort to see if this was a contributing source of variability, the monitors were grouped according to the dates of calibration provided by the manufacturer. There were four groups of at least four monitors each where the monitors in each group were calibrated together. The COV values for the measurements in this study for these four groups ranged from 1.7% to 2.7%. So, all four groups of monitors exhibited COV values less than of 3.4%. This is a clue that one possible way of reducing the variability in future studies is first to calibrate all of the monitors involved in the study together in one calibration run in the BMI chamber. Further, this calibration should be performed in a manner to keep the theoretical COV values due to counting statistics low; for example, less than 1%.

There was no deliberate effort to randomize the placement of the monitors on the various shelves in the chamber. Rather, they were pulled from boxes by three persons, and placed on the shelves in no particular order. While this may seem random, it is possible that there was some order in which the monitors were placed in the boxes in the first place. This “nonrandom” placement of monitors could have shown up as an effect that was confounded with one of the sources of variability being studied. For example, if the statistical analysis had shown that there was a significant difference among the shelf units, it might have been possible that this difference was caused by the manner in which the monitors were assigned to the shelf units and not due to nonuniformity of radon concentration in the chamber. This did not occur, so it appears that the nonrandom assignment of the monitors to the shelves had no effect. However, in any future studies, a deliberate procedure should be used to assign the monitors to the shelves in a random manner.

Further, if the statistical analysis had shown that there is significant variation of radon concentration in the chamber, the assumption mentioned above that the two monitors placed on each shelf were subjected to the same radon concentration might come into question. However, since the analysis did not show any significant variation of radon concentration, the assumption appears to be valid.

CONCLUSIONS

The results of this study indicate that no nonuniformity of radon concentration throughout the shelves in the BMI chamber was detected. The variability among the 36 continuous radon monitors used in the study was greater than any nonuniformity of radon concentration that might exist in the chamber. If there is nonuniformity of radon concentration among the shelves in the chamber, it must be so slight as to be difficult to detect. In order to improve the chances of detecting any such nonuniformity in future studies, the agreement among the devices used to measure the radon concentration must be improved. Because it appears that the fact that the monitors were calibrated at different times contributed to the variation among them, a possible way of improving the agreement would be to calibrate all the monitors together in the BMI chamber before using them in a nonuniformity study. Also, in future studies a deliberate procedure for assigning the monitors to the shelves in a random manner should be used.

REFERENCE

Ostle, Bernard, Statistics in Research, Second Edition, The Iowa State University Press, pp.316 – 321, 1963.

ACKNOWLEDGMENT

The author thanks the personnel from femto-TECH, Inc. for supplying the continuous radon monitors used in this study and for helping with the placement, retrieval and readout of the monitors.