Fernald Radon Stack Monitor User's Guide

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Introduction

The stack monitor uses long-range alpha detection (LRAD) technology for the measurement of radon levels in the stack emissions. The basic principle behind LRAD is the collection of ions created in air through the energy loss mechanisms of decay alphas[1]. This is accomplished by establishing an electric field in the region where alpha decays will occur, and directing the ions via the field onto a biased plate. Accumulation of charge on the plate results in a current in the biasing circuit which can be read with a sensitive electrometer. In electrostatic LRAD designs, the linearity of the measured current with gross alpha activity is well-established.

In order to determine radon-222 levels in the presence of other radon isotopes, it is necessary to perform some type of isotopic analysis on the stack samples. In the present case, other radon isotopes of possible concern are radon-219, which occurs in the decay chain of uranium-235, and radon-220, found in the decay chain of thorium-232. Radon-219, with a half-life of four seconds, presents no difficulty for the situation in which emanations from the vitrification process undergo as little as one minute of delay before release into the stack. For example, an initial concentration of 200,000 pCi/l of radon-219 decays to 5 pCi/l in one minute. Radon-220, however, has a half-life of about 55 seconds. If initially present in a substantial ratio to radon-222, a radon gross-alpha measurement on stack emissions would have a significant error if used as a measure for radon-222, even with many minutes of processing delay before the sample was taken.

For this reason, the stack monitor was designed to have two gross-alpha detection chambers with a delay chamber between them. Knowledge of the flow rate of the continuous stack sample through the monitor allows discrimination between radon-222 (hereafter referred to as radon) and radon-220 (hereafter referred to as thoron).

Figure 1 shows a schematic of the stack monitor. The continuous stack sample enters the monitor through either of the 1/4 inch swagelock ports (the monitor's design is entirely symmetric) set into the endplates. Just beyond the entrance is a baffle to disperse the airflow, which at the design criteria of 2 SCFM transported through 1/4 inch tubing would be entering the monitor at several hundred feet per minute. After this baffle, a thin filter attached to a steel grid further modifies the flow to provide a generally flat velocity profile throughout the actual detector volume. A similar filter is in place just beyond the detector volume. A delay length then causes about 75% of any thoron present in the first detector volume to decay by the time it reaches the second.

Figure 2 shows a detail of one of the detectors. Filter assemblies on either side of the detector volume are intended to provide a uniform airflow through the detector. The actual velocity profile of the airflow within the volume is of lesser importance than insuring that the airflow is identical in the two detectors. Three grids between the filters are used to collect ionized particles. Each grid is a circular stainless steel plate 0.06 inches thick, perforated with 1/8 inch diameter holes to give 40% open area in the plates. The grids extend to nearly the inner diameter of the pipe, where they are suspended from the inner walls with Lexan standoffs. The two outer grids, each 4 inches from the center grid, are placed at +300 VDC, while the inner grid is connected to ground through a Keithley 6517 electrometer.

Figure 1: Schematic of the radon/thoron monitor

Figure 2: Cutaway view of one of the detector volumes. Not shown is a grid/filter assembly, identical to the one in the figure, that is situated on the left hand side of the detector assembly.

When radon or thoron enter the spaces between the grids, the electric fields direct negative ions created from alpha decays onto the positive-biased grids. Positive ions are directed both onto the grid at ground (signal grid) and the walls of the detector. Figure 3 shows a cross-section of the azimuthally symmetric equipotential surfaces between the grids, and indicates the approximate region from which positive ions would be collected by the signal grid.

Figure 3: Cross-section through center of one of the detector volumes, showing the variation of electric potential with endplates at 300 VDC. The "active" region is the volume from which positive ions will reach the signal grid.

When an atom of radon undergoes alpha decay, the daughter is generally left with a net positive charge and will also be deposited on either the detector wall or the signal grid. Over time, this effect results in the accumulation of radon daughters within the detector volume that contribute to the observed alpha activity. For instance, radon has in its decay chain Po-218 and Po-214, each of which decays by alpha emission. By determining the contribution to the signal of these daughters, their effects can be accounted for and subtracted from the total signal.

The operation of the monitor is controlled by computer code. When executed, the code performs all necessary initialization of the electrometer over an RS-232 line, reads the current in the two detectors in sequence, then performs calculations using these signals to extract the radon and thoron concentrations present in the first detector. The results are printed to a computer monitor screen and written to files.

In order to achieve a good signal-to noise ratio while detecting radon levels of as low as 20 pCi/l, it is necessary to have a sufficiently large decay volume from which ions produced through alpha decay are collected. Noise from external ionization sources (e.g., cosmic background) is fairly proportional to the size of the volume and is on the order a few fA/l. Radon decays via emission of a 5.5 MeV alpha particle, which creates about 157,000 ion pairs as it loses energy in the surrounding medium[2]. In the absence of any ion loss mechanisms, 20 pCi (or 44 dpm) of radon will then generate around 18 fA of current when all the ions are collected in an LRAD device.

In practice, this maximum collection efficiency is not obtained. Ion loss occurs through columnar recombination along the alpha ionization track, ion-ion recombination after diffusion away from the track, and capture by the inner surfaces of the detector. Columnar recombination losses are straightforward to deal with, since over a wide range of ambient ion density they result in a constant fractional loss of initial ionization[3]. This is evidenced by the observed linearity of response of various LRAD detectors with source strength. With airflow detectors that rely on physically transporting ions to a collection grid, factors such as the geometry of the detector and velocity of the airflow complicate the apriori determination of ion losses. The complications become more severe as airspeed (and hence air turbulence) increases. Furthermore, ion-lifetimes in airflow designs are a function of the position along the pipe at which they are created. With radon and thoron, alpha decays occur at all positions within the detector.

Much of this complexity is avoided by the use of an electrostatic design. Although the stack monitor makes use of airflow to supply the stack sample, its inner diameter of 10 inches results in an average airspeed of about 3.7 fpm at 2 SCFM, and with a biased-to-signal grid spacing of 4 inches, ion movement is then dominated by the electric field. The total detector volume is 10.3 liters with an effective volume (or region from which ions will be collected onto the signal grid) of about 4 liters. With this arrangement, a concentration of 20 pCi/l of radon will produce approximately 60 fA of current.

Similar performance could be achieved with a detector of smaller dimensions by changing the polarities of the grids within the detectors. This would give field lines that collect virtually all ionization created inside the detector onto a signal grid at 300 VDC, and this is in fact a usual design feature of LRAD detectors. The drawback is a signal near 300 V, which requires the signal processing components of the electrometer to float above ground. Since size was not an important consideration for this application, it was decided to use the current design to lower chances of accidental contact with the 300 V source.

Theory of operation

The signals from the two detectors are considered to be due to external background sources, radon, thoron, and their radioactive progeny. Background signals over several days show only small variation with time and can thus be treated as constants. The decay of radon and thoron produce immediate contributions to the signal as well as delayed contributions from subsequent decays of their plated daughters. Because of the different decay alpha energies of the various isotopes involved, radon and thoron must be treated

somewhat differently when calculating their concentrations in the sample. The calibration for radon and thoron also differ because of the decay of thoron within each detector. At a nominal flow of 3.7 fpm, thoron that enters detector 1 requires about 10 seconds to traverse its 8 inch length. The thoron concentration at the exit is then only about 90% of that at the entrance.

Radon decays by emitting a 5.49 MeV alpha particle, while a thoron decay produces a 6.29 MeV alpha, followed almost immediately by a 6.78 MeV alpha from the decay of the daughter Po-216. Thus the signal from a given amount of radon activity will yield a lower signal than the same amount of thoron activity. The ratio of the signals is not simply the ratio of the alpha energies, due to the geometry of the detector and the effective collection region. However, using sources that produce known activities per time of radon and thoron, the constants relating activity/volume to signal from the detector can be determined.

A signal from radon or thoron will be a linear function of its concentration, and hence of the number of decays that occur. It follows that the number of daughters plated per unit time within the detector is proportional to the signals from radon isotopes. Once known, the proportionality factor allows for computational "tracking" of the background signals due to the daughters.

The process of data acquisition and computer analysis can be summarized by the following sequence of events which are controlled by computer code:

- (1) Electrometer reads current first in detector 1 and then in detector 2.
- (2) Background contributions from daughters plated within the detectors are subtracted from these readings to obtain signals due to radon/thoron.
- (3) Radon/thoron signals are converted to units of pCi/l and printed to screen and saved to file along with local time information.
- (4) New background levels are calculated from deduced radon/thoron levels.
- (5) Repeat (1)-(4).

Noting first that the long half-life of radon (3.8 days) results in no sensible loss of radon concentration between the two identical detectors, we have equal contributions to both signals from radon and its plated daughters. Any difference between the two signals will be due to thoron decay. The thoron will decay to Po-216, which has a half-life of 0.16 seconds. This isotope also decays by alpha emission to Pb-212, which plates out within the detector. The eventual decay of Pb-212 to the stable Pb-208 produces in its decay chain one alpha. With this information, we let

Sig 1 = raw signal from detector 1
Sig 2 = raw signal from detector 2
 λ = inverse mean life of thoron
t = transit time from detector 1 to detector 2
Rad 1 = *Rad 2* = radon contributions to signals
RadBack 1 = *RadBack 2* = radon daughter contributions to signals
Thor 1(2) = thoron contribution to detector 1(2)
ThorBack 1(2) = thoron daughter contributions to detector 1(2)

Here, *Sig 1* and *Sig 2* are the results of subtracting external backgrounds from the raw signals, and applying a normalization factor to account for any asymmetry between the overall collection efficiencies of the two detectors.

The thoron and thoron daughter contributions are related by

$$Thor2 = Thor1 \times \exp^{-\lambda t}, \text{ and}$$

$$ThorBack2 = ThorBack1 \times \exp^{-\lambda t}.$$

Since

$$Sig1 - Sig2 = (Thor1 + Rad1 + Thorback1 + Radback1) - (Thor2 + Rad2 + Thorback2 + Radback2), \text{ we have}$$

$$Sig1 - Sig2 = (Thor1 + Thorback1) \times (1 - \exp^{-\lambda t}).$$

The transit time t used here is the effective time for thoron to pass from detector 1 to detector 2. The average linear speed u_{av} of the flow is equal to (volume flow)/(cross-sectional area), so at a volume flow of 2 SCFM, u_{av} is about 3.7 fpm. With this geometry, the airflow between the detectors approaches a parabolic velocity profile as it nears detector 2 with a maximum speed along the axis of nearly twice the average airspeed. Much of the mass flow occurs, then, at speeds greater than the average and experiences less decay. Although some of the mass flow occurs at less than average airspeed, the net result is that the amount of decay seen at detector 2 is less than would be assumed using only the average airspeed so that $t < t_{av}$.

While the effective transit time is best found by using a thoron source and observing the amount of decay seen between the detectors, a good approximation can be calculated from the equations for the radial velocity $u(r)$ [4]

$$u(r) = \beta(R^2 - r^2) \quad ; \quad u_{max} = \beta R^2 \quad ; \quad u_{av} = 2\beta,$$

where R is the inner radius of the pipe. These equations hold for airflow in circular pipes in which the final state velocity profile has been achieved (Poiseuille flow). Although the final state profile is only asymptotically reached, the expected airflow through the monitor has a Reynold's number of ~ 200 so that after several feet beyond detector 1, the velocity profile is already approximating the final state. Figure 4 shows the results of a computer code written to add contributions from different radii in the pipe, each of which experiences decay based on the airspeed at that radius. At an average speed of 3.7 fpm, the effective airspeed is 4.7 fpm, in good agreement with thoron measurements at a volume flow of 2 SCFM. The conversion from actual average velocity to apparent velocity is

$$apparent \text{ velocity} = 0.582 + 1.11 \times average \text{ velocity}.$$

By knowing the initial backgrounds in the detectors from radon and thoron, the computer code can extrapolate the background at later times so that we can calculate the radon and thoron concentrations in the first detector using the relations

$$Thoron = \rho_t \left[\left(\frac{Sig1 - Sig2}{1 - \exp^{-\lambda t}} \right) - Thorback1 \right] \text{ and}$$

$$Radon = \rho_r (Sig1 - RadBack1 - Thor1 - Thorback1).$$

Here, ρ_r and ρ_t are factors that relate the raw signal contributions of the radon and thoron to activities in pCi/l. In addition, the factor ρ_t accounts for the immediate decay of the thoron daughter Po-216.

Figure 4: Results of a calculation of apparent versus average airspeed assuming Poiseuille flow through the length of the decay volume.

We can break up the ρ 's into their constituent parts as follows:

$$\rho = \gamma \left[\alpha \text{ energy (MeV)} \times 10^6 \frac{\text{ev}}{\text{MeV}} \times \frac{1 \text{ ions}}{35 \text{ ev}} \times \left(1.602 \times 10^{-19} \frac{\text{C}}{\text{ion}} \right) \times 10^{15} \frac{\text{fA}}{\text{A}} \right]^{-1},$$

which reduces to

$$\rho = \frac{\gamma}{4.78(\alpha \text{ energy})},$$

with γ in pCi/dps. The determination of the γ 's for radon and thoron is part of the calibration of the monitor, and is accomplished by using known concentrations to produce a signal in the detectors.

To find the daughter background contribution to the signals, we first derive a number N for the number of radon or thoron atoms in the detector by calculating the activity in dps (e.g., thoron activity = Thoron/γ), so that

$$N_{\text{thoron}} = \frac{\text{Activity}_{\text{thoron}}}{(1 - \exp^{-\lambda_{\text{thoron}}})},$$

where λ is in inverse seconds.

There are two incremental contributions in the calculation of the number of daughter atoms of a given isotope: an increase from the decay of the parent and a decrease from decay of the daughter atoms already present. Assuming a constant concentration of the parent species, the increase in the number of atoms N is governed by the relation

$$\frac{dN_2(t)}{dt} = \lambda_1 N_1(t) - \lambda_2 N_2(t)$$

where the subscript 1 and 2 refer to the parent and daughter species, respectively, and the λ 's are inverse mean-lives. The daughter decay causes a loss of already present atoms at a rate

$$\frac{dN_2(t)}{dt} = -\lambda_2 N_2(t).$$

From these contributions we can calculate the number of daughters at time $t+\Delta t$ as

$$N_2(t + \Delta t) = \frac{\lambda_1}{\lambda_2} (1 - \exp^{-\lambda_2 \Delta t}) N_1(t) + \exp^{-\lambda_2 \Delta t} N_2(t).$$

The activity A of the daughter in disintegrations per second is

$$A_2(t) = (1 - \exp^{-\lambda_2}) N_2(t),$$

where λ_2 is in inverse seconds. The signal S from the daughters is then

$$S_2(t) = A_2(t) \times \text{energy of alpha} \times \text{efficiency} \times \text{conversion factor}.$$

The conversion factor is a numerical constant to give S in units of fA.

When the parents are radon or thoron, their number $N_1(t)$ need not be known absolutely -- it is sufficient to assign a number proportional to the signal they produce. A subsequent efficiency factor accounts for the uncertainty of the actual number. The efficiency factor is a function of alpha energy, and so must also account for effects due to the path lengths of decay alphas. The positively charged daughters of radon and thoron are deposited both on the signal grid and on the walls of the detector. Many of the alphas emitted from the plated daughters on the signal grid will not lose all of their energy in the effective collection volume of the detector, while some alphas from daughters plated on the detector walls will lose some of their energy there. It can be seen from the shape of the effective collection region that an increase in alpha energy from sources plated on the signal grid will have relatively mild effects on the amount of ionization collected, while for sources plated on the detector walls an increase in alpha energy will allow substantially greater penetration into the effective collection region. These effects are difficult to calculate accurately, but can be measured by fitting the decay curves of the plated daughters after the detector signal has achieved equilibrium with a source of radon or thoron.

The decay schemes of radon and thoron are shown in Figure 5. After reading the current from detector 1 and detector 2, the computer code updates the new values for the number of relevant decay products inside the detectors using the formula

$$N_{n+1}(t + \Delta t) = \frac{\lambda_n}{\lambda_{n+1}}(1 - \exp^{-\lambda_{n+1}\Delta t})N_n(t) + \exp^{-\lambda_{n+1}\Delta t} N_{n+1}(t),$$

and then their signal contributions S_{n+1} , as before. The individual contributions from the radon and thoron daughters in each detector are then summed to give the plated daughter background signals in each detector. This process is repeated at intervals of length Δt , which is the interval of time required for the scanning electrometer to obtain a current measurement from both detectors.

Figure 5: Decay schemes for Rn-220 and Rn-222.

Test results

Testing of the monitor was limited by the availability of radon and thoron sources. Most results were obtained using thorium ore specimens which supplied approximately 500 pCi/sec of thoron. At the airflows used (generally near 2 SCFM, or ~1 l/sec) the concentration was about 500 pCi/l. In long test runs in several prototype monitors, both airflow and electrostatic, the source showed diurnal fluctuations in thoron output which were attributed to temperature fluctuations.

Figure 6 shows a run in which there are initially only background levels of radon present. A regulated compressed air supply created the airflow through the monitor. The thoron source was then placed in a pipe just upstream of a HEPA filter so that the monitor would see only background ionization and that due to thoron and its progeny. The figure shows the immediate rise in signal of the first detector, followed closely by a lesser rise in the signal of detector 2. The slow initial decrease in both signals is attributed to a decrease

in the thoron output of the source. The decrease is reflected in the calculated thoron and radon levels, shown in Figure 7. The statistical error in the calculations, using the 2.5 minute effective time averaging in the code, is $<5\%$ for concentrations as low as 200 pCi/l. The small spikes seen at the point of insertion of the thoron source is due to the invasive nature of the method of insertion, which required temporary disruption of the airflow.

Figure 6: Signals in the two detectors from a thoron source. At around 5:00 PM the source is placed in the airstream

Figure 7: Concentrations of radon and thoron calculated from the data of Figure 4.

The relative contributions from the daughter Bi-212 (33% decay via a 6.07 MeV alpha to Tl-208 and 67% decay to Po-212, which decays immediately via a 8.78 MeV alpha to Pb-208) were determined from fitting the decay curve of a run of sufficient length for the thoron daughters to reach equilibrium. Figure 8 shows the signals in both detectors after the daughters have reached equilibrium with the source. The point at which the thoron source is removed is easily visible, as is the subsequent decay of the plated daughters. By subtracting the signals obtained immediately after the source is removed from the signals just before its removal, we get the signal due to the thoron source alone. The ratio of the pure background signal to the pure thoron signal gives the factor relating their relative contributions. In the code, this factor is modified by the alpha energies of the decay products.

Figure 8: Signals from both detectors showing initial equilibrium of thoron daughters and their subsequent decay after the source is removed just before 9:00 AM.

A similar procedure was performed using the available radon source, which was a specimen of natural uranium ore. The specimen was found to emit approximately 4 pCi/sec of Rn-222. Natural uranium contains only small amounts of U-235, from which Rn-219 is derived, but it produces a considerably greater activity of Rn-219 than Rn-222 due to its short (~4 seconds) half-life. To eliminate the Rn-219, a long (~2 minutes) delay line was placed between the source and a prototype detector, and the airflow from the compressed air source was adjusted using a regulator. By reducing the flow, a much larger concentration of Rn-222 was able to be examined. The daughters of radon are fairly short-lived (<30 minute half-lives) so equilibrium could be achieved after only a few hours.

Figure 9 shows data from the radon source taken in this manner. Throughout the first part of the run, the airflow was periodically reduced slightly to attain ever higher levels of Rn-222. At 3:00 PM on the plot, the airflow was increased slightly to lower the radon concentration to a level that would be in equilibrium with the daughters plated thus far. After observing that the signal had reached a plateau, the source was removed and the airflow increased in order to quickly flush the system of radon. By adjusted the parameters of the code to fit the decay curve, relative strength factors were found for the radon daughters.

Figure 9: Signal in prototype detector from radon source. The signal was caused to reach equilibrium (see text), and the source was then removed at about 4:00 PM.

The factor for the thoron daughter Bi-212 was found to be 0.55. This factor multiplies the weighted average energy of 7.87 MeV of the two alpha decay pathways mentioned earlier. Fitting the decay curve of the radon daughters gave the factors 0.405 for Po-218 and 0.515 for Po-214. These factors also multiply the respective alpha energies of the respective isotopes to yield their signal contributions as they plate out within the detectors.

The relative strength factors for the daughters and the conversion factors for radon/thoron signals to radon/thoron concentrations will differ from these when the atmospheric pressure at which the monitor operates is changed substantially. At Los Alamos, New Mexico, where these measurements were taken, the pressure is around 11.5 psi. Near sea level, atmospheric pressure is near 15 psi, and alphas of a given energy will have a shorter range there. As described before, the geometry of the detectors and the field lines generated within them alter the efficiencies of ion collection by the detector grid in a manner dependent on the alpha range. It is necessary in any case to calibrate the monitor with known sources, and the relative strength factors for the daughters can be extracted from the same data.

The algorithm for the computer code has been tested for stability using simulated data. The data was generated at the same time intervals as that produced by the actual monitor and a gaussian error is introduced of the same magnitude as observed in actual data. When using the code to determine the radon and thoron concentrations from the simulated data, scenarios were created by supplying the code with inaccurate initial or operating conditions. One situation of interest is when significant background signals due to daughter plating are present in the detectors, while the code is initiated with background levels equal to 0. In simulating this scenario, the airflow was set to be 2 SCFM with

20,000 pCi/l of radon and 10,000 pCi/l of thoron, and the code was allowed to generate four days of data. The radon and thoron concentrations were chosen to reflect maximum estimates of their possible activity ratios. Figure 10 shows the simulated data over the fourth day when background contributions had reached equilibrium with the radon and thoron levels. The data shown is time averaged over one minute intervals. Figure 11 shows the results of running the code with the data of the fourth day as input. After two hours, the code converges to the correct value for the radon concentration. The thoron concentration takes longer to approach the correct value. The times for the calculated radon and thoron concentrations to reach the correct values in this simulation are closely related to the dominant half-lives of their respective decay products; i.e., the 27 minute half-life of Pb-214 for radon, and the ~11 hour half-life of Pb-212 for thoron.

Figure 10: Simulated data assuming initial radon concentration of 20,000 pCi/l and 10,000 pCi/l of thoron at 2 SCFM. Data shown is fourth day of run, where radon/thoron daughter activity has reached equilibrium with activities of these concentration.

Figure 11: Results of running code using the data of Figure 10. Initial conditions are assumed to be an airflow of 2 SCFM and no signal due to daughter plating. The code converges on the true value for radon within a few hours. True thoron levels are asymptotically reached with a half-life of ~11 hours.

Another simulation creates data with the same radon and thoron concentrations as before, starting with no background plating present. The airflow is initially set to be 2 SCFM, but then is given a sin wave variation in time with a two hour period, imposing a $\pm 10\%$ variation in the average airspeed. The one minute time-averaged data over a one day period is shown in Figure 12. Detector 2 has fluctuations due to the varying decay time available to the thoron. Figure 13 shows the results of running the code to unfold the radon and thoron concentrations while assuming a constant airflow of 2 SCFM. Both concentrations have a $\pm 5\%$ variation around their correct values as a consequence of assuming a constant airflow existed. The variations would decrease in magnitude as the relative concentration of thoron was decreased.

Figure 12: Simulated data assuming radon/thoron concentrations as before, with a 10% sin wave variation in the 2 SCFM airspeed.

Figure 13: Code analysis of the data of Figure 12 shows ~5% variation around the true radon/thoron values. The magnitude of the variations is tied to the actual thoron levels.

To investigate the effects of uncertain values of the relative strength factors for the plated daughters, simulated data was created using factors 10% less than those cited above. The radon/thoron concentrations are as before and the airflow is a constant 2 SCFM. The one-minute time averaged data for this simulation is shown in Figure 14. Figure 15 shows the unfolded radon and thoron concentrations assuming the experimentally determined relative strength factors. The radon concentration is found to be 5% lower than the actual value. The decrease is insensitive to the thoron concentration, as shown in other simulations where the thoron concentration is varied. The calculated thoron levels also show about a 5% lower value than the actual ones after a time equal to several mean-lives of the thoron decay product Pb-212.

Figure 14: Simulated data assuming relative strength factors for daughters (described in text) 10% lower than the experimentally determined values. Airspeed and radon/thoron concentrations are as in Figure 10.

Figure 15: Analysis of the data of Figure 14. Radon levels are ~5% lower than actual values, with similar results for thoron asymptotically reached with a half-life of ~11 hours.

Assembly of monitor

The documentation supplied with the stack monitor includes detailed blueprints. The monitor has been broken down into two straight sections, each containing a detector unit, and the "U" section that serves as part of the delay volume. The two straight sections have been stamped with the letters "A" and "B" that are to be matched with their counterparts on the "U" section to obtain the correct alignment. It is recommended that a thin layer of sealant such as RTV silicone be applied to the pipe ends to be joined to ensure a proper seal.

The monitor should be mounted to existing infrastructure with support provided on both straight sections. The flanges that connect the various pipe sections are not intended to support the weight of the monitor. In addition, the orientation of the monitor should allow the attachment of a flat surface on which the electrometer and battery will stand. The straight section labeled "A" has at its entrance a 1/4" swagelock fitting for receiving the stack sample. The "B" section has the same fitting for recycling the sample back into the stack. When assembled in this manner, the six triax connectors on the detector units will be facing toward the centerline of the monitor.

CAUTION: Extreme care should be used when handling and fixing in place the 300 V battery, and when making connections between it and the monitor assembly to avoid electrical shock.

Before any electrical connections are made, it should be determined with a continuity check that the center pins of all triax connector on the monitor and the supplied cables are isolated from the inner rings and from ground. Four of triax connectors on the monitor are labeled "300 VDC" and are to be connected to the positive terminal of the 300V battery with the triax cable assembly marked "300 VDC". The ground terminal of the battery should be connected to the "common" terminal on the back of the electrometer with the cable labeled "battery ground (-)". It should be verified that the common terminal is connected to the electrometer chassis ground, that the three-prong electricity plug for the electrometer is properly grounded, and that the appropriate line voltage for the electrometer is selected.

The electrometer is equipped with a ten-channel scanner card, only two of which are used in this application. One of the signal cables should connect the triax connector marked "signal" on section "A" to input 2. The other signal cable should connect the triax connector marked "signal" on section "B" to scanner input 5. The scanner card cable labeled "output" should be attached to the electrometer input connector. The scanner inputs 2 and 5 should be used since they have been found to have the fastest settling times, and have been specified in the computer code as the channels to be scanned.

The electrometer is supplied with a temperature probe and a relative humidity probe for external measurements. These attach to labeled connectors on the back of the electrometer. While they are optional to the operation of the monitor, they can monitor for appropriate environmental operating conditions for the electrometer.

The final connection to the electrometer is an RS-232 connection to a PC-compatible computer which can be located a considerable distance from the monitor (check specifications for the cable employed). The electrometer requires a nine-pin connector, and the cable should be wired straight-through (not null-modem) to the COM2 port of the computer.

The electrical components should reside inside an enclosure for protection from the environment. While the electrometer was chosen partly because of its wide range of acceptable operating conditions (0-50 degrees C, relative humidity 70% non-condensing), it is not waterproof. The current load on the battery is very small (maximum drain at 200,000 pCi/l of radon and thoron $<10^{-7}$ A), so the battery should be unaffected by normal temperature extremes. It is possible to use plastic hose clamped and sealed around the monitor's triax connectors, through which the cables would run up to the electrical parts, so that only the electrometer and battery would need to be protected.

Operation of monitor

After the monitor is assembled and connected to a PC-compatible computer and the source sample supply line, but before the sample is allowed to pass through the monitor, the files "back.exe" and "comp.exe" should be copied from the supplied 3.5" diskette into the desired directory of the computer. A background level should then be taken on the two detector volumes by running the program "back.exe". This program will run for several minutes and then write the background levels to the file "back.dat". The program "comp.exe" may then be run.

"Comp.exe" is the main program, and after reading in the background levels for subtraction from the detector readings, it begins taking successive readings from the two detectors for calculation of radon and thoron levels. The on-screen output is a running display of time, radon level (pCi/l), thoron level (pCi/l), external temperature, and external relative humidity. All readings are referenced to the first detector. The same data is written to a file with a filename in the format "month_day.dat". An additional file is written containing time and raw signals from the two detectors, and has a filename in the format "month_day.sig".

The current version of the program cannot always immediately recover from interruption. Daughter background levels are continuously written to a file for use when the program is temporarily terminated and at automatic re-initialization that occurs at 12:00 PM each day as new files are created for the daily logs. Abnormal termination, however, (such as loss of power) will result in loss of the continuously updated background file as well as the current log files. The previously saved version of the daughter background file will be read in upon restart of the program, with a resultant probable error in calculated radon and thoron levels. True readings will be recovered on a time scale as described in the section on test results.

The program can be modified to include support for abnormal termination of the program, such as preventing loss of files. It is also possible to include capability of user input that would allow, upon resuming the program after normal or abnormal termination, inclusion of factors such as length of time the system has not been operating and estimated levels of radon and thoron that have passed through the detector while the program was not executing. This capability could greatly reduce the time necessary to achieve accurate calculated radon and thoron concentrations.

Calibration procedures consist of several steps. The first is the examination of a known concentration of radon running through both detectors for a sufficient time (~1-2 hours) to allow substantial background plating, then removal of the source to collect data for a similar length of time to observe daughter decay. A normalization constant is determined that multiplies the signal of detector 2 to give identical signals from both detectors. This factor is called "NORM" in the code. By fitting the data through a simulation, the relative strength factors for the plated daughters can be found. These are input into the "EFF" matrix in the code. Finally, the calculated and actual concentrations are compared to yield the factor "RADPCI" for the code, which is the factor γ described in the section "Theory of operation". A known thoron source is then used in the same manner to obtain efficiency factors for the daughters and the thoron g factor, called "THORPCI" in the code. The ratios of the thoron signal in the two detectors are used to provide the effective transit time "LEN". This is found from the relation

$$LEN = -80.2 \ln \left(\frac{Sig2}{Sig1} \right),$$

where 80.2 is the mean life of thoron in seconds.

Determining the factors NORM, LEN, THORPCI, RADPCI, and the EFF matrix and placing the values into the code completes calibration of the instrument.

The battery should be checked periodically for discharge. Currents drawn in LRAD devices are very small so that battery life is essentially its shelf life, and detector response is only weakly dependent on the battery voltage for voltages near 300VDC, but eventual weakening of the battery will require its replacement.

References

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