Abstract

The Radometer measures radon and thoron by electrostatic collection of charged progeny on a surface barrier detector. Accurate measurements are made in only a few minutes because this instrument uses a dual electric field configuration, thus eliminating filters which slow the response time. An on board computer corrects for the effect of moisture and previous deposition to maintain accuracy and fast response when the instrument encounters high humidity and/or rapid changes in concentration. The instrument's detection volume is 6 L and its efficiency is 25% or 0.041 cpm per Bq m\(^{-3}\) (1.5 cpm per pCi L\(^{-1}\)).

I. INTRODUCTION

The capability to rapidly measure environmental levels of radon and thoron with a portable hand-held instrument can fulfill an important role in both the routine assessment of indoor radiation fields and it can also be used as a research tool for studying the movement of radon and thoron into and through various building types. Thoron measurements are of considerable interest as a research tool because it may be a much more specific indicator of noble gas ingress into dwellings due to its much shorter half-life. In this paper we describe a new instrument (Radometer: radon + meter) which utilizes an electrostatic collection technique, and which allows accurate measurements of environmental radon at Environmental Protection Agency action level guideline of 148 Bq m\(^{-3}\) (4 pCi L\(^{-1}\)) and above in \(<10\) min.

The measurement of radon by electrostatic collection of charged progeny has been reported previously. Costa-Ribeiro et al. [1] developed a 28 cm\(^3\) detection chamber in which an electric field was used to deposit progeny on an alpha sensitive photographic plate. Wrenn et al. [2] increased the volume to 1 L and registered alpha activity with an alpha scintillator and photomultiplier tube. By collecting the progeny on a solid-state surface barrier detector, Negro and Watnick [3], in their Funghi instrument, were able to analyze the progeny using spectroscopic techniques. In principle, this last technique permitted a rapid measurement of radon concentration by counting only the short-lived \(^{218}\)Po, which builds up with a 3 min half-life. However, this could not be achieved with the Funghi because it, as well as the other two instruments, uses a front filter. This front filter is open pore foam and insures that only radon gas enters the decay volume. But the response time was greatly slowed because the diffusion through this foam takes over a half hour. In addition, another significant problem with these types of instruments is that they perform poorly in humid environments since moisture interferes with the electrostatic collection process by neutralizing the charged progeny.

The Radometer addresses these problems by measuring and correcting for moisture, and by using a dual electric field configuration which eliminates the need for a filter. The moisture correction is made with a small on board computer that also stores data and performs several other tasks. The Radometer has four counting channels. Two of these channels are used for counting alpha particles from the decay of radon (\(^{222}\)Rn), and the remaining two are used to count alpha particles from the decay of thoron (\(^{220}\)Rn).

II. RADOMETER DESIGN

The Radometer is hand carried and is shown in Fig. 1. Its overall size is 28 cm in diameter by 30 cm high, and its weight is about 6 kg. The top 7 cm section contains the electronics, while the bottom is the detection assembly. This assembly, shown in Fig. 2, consists of three concentric cylinders. The outermost cylinder forms the exterior shell of the instrument and has two large cutouts, one of which can be seen in Fig. 1. The Radometer has four counting channels. Two of these channels are used for counting alpha particles from the decay of radon (\(^{222}\)Rn), and the remaining two are used to count alpha particles from the decay of thoron (\(^{220}\)Rn).
Fig. 1. Radometer instrument. After obtaining an air sample, the shutter is closed for detection and alpha counting.

Fig. 2. Detection assembly. This assembly consists of three concentric cylinders. One of them is movable and forms a shutter to block light.
Pulses from the 300 mm\textsuperscript{2} parent radon/thoron gas have a positive charge cylinder, while the surface barrier detector is kept at ground potential. Neutral progeny that enter the inner cylinder and undergo charged progeny. In addition, by also keeping the middle charged progeny in the incoming air from entering the innermost cylinder. This insures that only the charged \(^{216}\text{Po}\) or \(^{210}\text{Po}\) which form in the inner cylinder from the decay of the parent radon/thoron gas will be collected on the detector. Neutral progeny that enter the inner cylinder and undergo further decay will also be collected, but not as \(^{218}\text{Po}\) or \(^{216}\text{Po}\). Because of this dual field technique, no filter is required.

III. ELECTRONICS

The four channel counting electronics is shown in Fig. 3. Pulses from the 300 mm\textsuperscript{2} detector are amplified by a commercial charge sensitive amplifier (Amptek Inc., Bedford, MA 01750, Model A-225) and then sent to the counting channels. These channels register alpha counts from \(^{218}\text{Po}\), with an energy of 6.0 MeV, and \(^{214}\text{Po}\) (7.7 MeV), in the radon decay chain, and from \(^{210}\text{Po}\) (6.8 MeV) and \(^{212}\text{Po}\) (8.8 MeV), in the thoron decay chain. Thoron also produces \(^{212}\text{Bi}\) which is produced in an approximate 2 to 1 ratio which permits a correction to be made. As an example, if 50 counts are registered in the \(^{212}\text{Po}\) channel, then half or 25 must be subtracted from the \(^{218}\text{Po}\) channel to correct for the contribution of \(^{212}\text{Bi}\). This correction is made by the on board computer.

The on board computer is a Tattletale Model 4 (Onset Computer Corp., N. Falmouth, MA 02556). It is programmable in BASIC and has extensive input/output (I/O) capabilities such as an 11 channel 10 bit analog to digital (A/D) converter, 16 programmable digital I/O lines, and an on board temperature sensor. Its memory is 32K which is used for programs and data. Power consumption depends on the BASIC instructions being executed and is typically 5-10 \(\mu\)A. In addition, its small size, 5 cm by 10 cm, makes it easy to incorporate in a compact electronics package.

Each counting channel consists of a threshold comparator, a modulo 16 counter, and a shift register. Counts from these channels are transferred in parallel to its associated shift register. Counts from these channels are transmitted to the computer via a serial data line. Software in the on board computer perform the subtractions necessary to convert the threshold comparator function to a window comparator function. The threshold for the lowest energy channel, which registers 6.0 MeV alpha counts from the decay of \(^{218}\text{Po}\), is set to a voltage corresponding to an energy of slightly more than 5.3 MeV to avoid counting the smaller \(^{216}\text{Po}\) contribution which will build up on surface barrier detectors after long exposure to radon. The setting for the second channel is set at a voltage corresponding to an energy between 6.0 MeV and 6.8 MeV but closer to 6.0 MeV. This allows for this is that 6.0 MeV is the maximum alpha energy from the decay of \(^{218}\text{Po}\), while degraded alpha particles considerably below the 6.8 MeV maximum from the decay of \(^{216}\text{Po}\) can occur due to the nonuniformity of the detector collection surface. Thresholds for the remaining two channels are set in a similar manner. The output of the amplifier is externally available for use with a multichannel analyzer (MCA) to check the settings of the threshold comparators. In addition, the Tattletale computer, via its A/D converter, monitors the voltage settings of the threshold comparators and will alert the operator if there is any drift. Tests have shown that there is no significant temperature drift in these settings over the range of -20\(^\circ\)C to +80\(^\circ\)C.

On command from the on board computer, data from the four counters are transferred in parallel to its associated shift register. The computer then generates a series of clock pulses to shift the data to the computer via a serial input line. This entire data transfer protocol is implemented with only a single BASIC instruction. In the computer, the data from all four counters are stored as a single modulo 16 integer. A software routine then operates on this integer to extract the individual

![Electronics block diagram](image-url)
counts associated with each of the four channels.

To correct for the effect of moisture, a small moisture sensing circuit (Thunder Scientific Corp., Albuquerque, NM 87123, Model PC-2101), which was modified for low power operation, is used. The sensor in this circuit is a thin film of noble metal whose electrical impedance changes when water dipoles interact with the lattice of the thin film. This impedance is then conditioned by the circuit to produce an analog voltage that varies as changes in moisture occur. The computer reads this voltage via its analog-to-digital converter and a correction, if necessary, is made to the count data.

A four character seven segment liquid crystal display (LCD) is used to show data and concentration results. This display is interfaced to the computer with a serial data line and three control lines [5] and consumes only 50 μA. Because of the seven segments (and decimal point), each character position is modulo 256. Therefore, to output a 4 digit number, the computer must first weight each digit with the appropriate modulo 256 exponent. Concentration results are displayed with a fixed decimal format so the displayed range is 3.7 to 37,000 Bq m⁻³ (0.001 to 9999.9 pCi L⁻¹).

Power is obtained from three flashlight battery ‘D‘ cells that supply two DC-DC converters, one for the high voltage module and the other for the remaining electronics and computer. These converters were designed for this application and will maintain operation as the battery voltage decreases from 4.5 V to 3 V. This is sufficient to power the Radometer for over 2 weeks when it is used 7 to 8 h daily. When power is removed, a small battery on the computer board maintains the BASIC program and the stored data.

IV. CALIBRATION AND TESTING

The Radometer was tested in the Environmental Measurements Laboratory’s radon, thoron and progeny exposure facility [6], using radon concentrations of 555 to 1850 Bq m⁻³ (15 to 50 pCi L⁻¹). These tests showed that the sensitivity for the measurement of ²¹⁸Po from the decay of radon is 0.041 cpm per Bq m⁻³ (1.5 cpm per pCi L⁻¹) or an efficiency of 25%. This efficiency refers to those alpha particles which are directed toward the detector (2 π collection) and assumes, for convenience, that all of the ²¹⁸Po is positively charged. In practice, 80 to 90% of the ²¹⁸Po is positively charged [4]. Our previous work with the Funghi instrument [3] has shown that half of the charged progeny are lost on the metal case surrounding a conventional detector such as the one used in the Radometer. The detector used in the Funghi had no case (ring mount) and achieved a collection efficiency of over 50% for ²¹⁸Po. Although it was not used initially because its mechanical mounting is more difficult than a conventional detector, it is expected that this type of detector will also be used in the Radometer. Preliminary tests indicate that the efficiency for the collection of ²¹⁶Po from the decay of thoron is also 25%. Since the half-life of ²¹⁶Po is only 0.15 sec, some further tests are necessary to confirm this result. If verified, it indicates that the collection process is much faster than 0.15 sec.

As the progeny are deposited right on the surface of the detector, the spectral resolution is very good and measures less than 70 keV full width at half maximum (FWHM). Noise from the DC-DC converters contributes significantly (almost half) to this figure, but even with this noise, all the spectral lines of interest are fully resolved.

V. HUMIDITY TESTS

To measure the Radometer’s sensitivity to moisture, tests were made in our radon, thoron and progeny exposure facility at several temperature and relative humidity conditions. The data obtained were then plotted on a psychrometric chart and confirmed the findings in reference [3]: namely, that the moisture response of electrostatic collection instruments is a function of absolute humidity. The moisture dependence for the Radometer is shown in Fig. 4. In the following discussion, the range in parenthesis is percent relative humidity (RH) at 30°C. From Fig. 4, the collection efficiency remains constant at approximately 25% when the absolute humidity is between 6 and 11 g kg⁻¹ (20 to 40 RH), it then decreases from 25% to 19% for 11 g kg⁻¹ to 24 g kg⁻¹ (40 to 80 RH), and then it falls very sharply for values > 25 g kg⁻¹ to 12% at 27 g kg⁻¹ (80 to 90 RH). The value of 6 g kg⁻¹ is the lowest humidity that could be achieved in our exposure facility. These calibration factors are programmed in the on-board computer so corrections can be made when required. However, because the slope of the curve in Fig. 4 is so steep above 24 g kg⁻¹, the computer, due to the poor counting statistics, cannot make an accurate correction and the instrument reads incorrectly, as it did in a recent field test under extreme humidity conditions.

![Humidity response](image-url)

Fig. 4. Humidity response. The nominal 25% collection efficiency of the Radometer decreases sharply above absolute humidity levels of 24 g kg⁻¹.
VI. RADOMETER OPERATION

When power is first applied to the Radometer, its software assumes that there is no $^{218}\text{Po}$ on the detector. As $^{218}\text{Po}$ is collected, the software calculates values for the exponential buildup equation and predicts the actual ambient radon concentration. Since this is done every few seconds, it allows the operator to observe the approximate radon concentration very quickly. The actual time required to make a more precise measurement is limited by the counting statistics. For example, a radon concentration of 370 Bq m$^{-3}$ (10 pCi L$^{-1}$) would register 30 counts in the first 5 min of buildup. Of course when the buildup is complete, after about 12 min, the same 370 Bq m$^{-3}$ (10 pCi L$^{-1}$) concentration would register 75 counts in a 5 min interval. As mentioned previously, the display indicates concentration directly in units of Bq m$^{-3}$.

A problem with other radon survey instruments is, in effect, short-term contamination of the detector which occurs when a measurement in a high concentration area precedes one in a low concentration area. However, with the Radometer, the user presses a button to initiate a new measurement. Using the superposition principle for exponentials, the software will then calculate the decay of any previous activity on the detector and subtract the corresponding counts. It then treats the resulting difference counts as due to newly deposited $^{218}\text{Po}$, and calculates the actual ambient radon concentration as before. Because of this, the instrument is not affected by moving the instrument from a high concentration area to a low concentration area. For example, if the radon concentration is reduced from 3700 to 370 Bq m$^{-3}$ (100 to 10 pCi L$^{-1}$), the instrument will show a reading between 296 and 444 Bq m$^{-3}$ (8 and 12 pCi L$^{-1}$) in $<2$ min.

Thoron activities, based on the measurement of $^{216}\text{Po}$, are calculated in much the same way as radon measurements. The half-life of $^{216}\text{Po}$, 0.15 sec, is short and thus does not require any buildup or decay calculations. However, unlike radon with a 3 day half-life, the half-life of thoron is only 55 sec. Therefore, once the shutter is closed, the thoron held in the 6 L chamber of the Radometer decays, and a correction must then be made. This correction is done in the software using a simple exponential function.

In addition to performing the aforementioned calculations of radon and thoron concentrations in air, the computer stores 1 min records of the counts in each of the four counting channels, the output of the moisture sensor, and the temperature. Its storage capacity allows for 3000 records along with hourly time and date information. This information can be read from the computer and permits a subsequent more careful analysis of the data if desired.

VII. DISCUSSION

A portable battery operated instrument which permits rapid measurements of environmental levels of radon/thoron has been described. It has been tested extensively and its operation is very reliable. Presently, the sensitivity is .041 cpm per Bq m$^{-3}$ (1.5 cpm per pCi L$^{-1}$), but it is expected, through the use of a ring mount detector, that the sensitivity can be increased to about .08 cpm per Bq m$^{-3}$ (3 cpm per pCi L$^{-1}$). Although the on board computer compensates for the effect of moisture, levels above 24 g kg$^{-1}$ remain a problem. To overcome this, we are now studying cooling techniques to remove moisture. If, for example, the incoming sample air is cooled to 10$^\circ$C before it enters the detection chamber, then the maximum water content is only 8 g kg$^{-1}$. The main difficulty is how to achieve this cooling with a limited battery budget. In addition to moisture, it has been reported that nitrogen dioxide can also cause neutralization of charged radon/thoron progeny [4]. This may be a problem in obtaining accurate measurements, particularly in kitchens with gas stoves. Studies are planned to quantify the effects of nitrogen dioxide on the performance of the Radometer.

Thoron measurement precision in the Radometer can be improved. In its present configuration, the thoron sample is held in the detection chamber, but this sample can only be counted for a few minutes before the thoron completely decays. In many cases, particularly at low concentration levels, this is not sufficient to obtain an accurate reading. If the detection chamber configuration were changed to accommodate a gentle flow of external air, perhaps by using a small fan, ambient thoron would continuously reside in the detection chamber.

Recently, software techniques have become available which permit computer modeling of electric fields with different boundary configurations (Ansoft Corp., Pittsburgh, PA 15219, Maxwell electrostatics package). For a given collection voltage, studies of electric field configurations could help to increase the volume while maintaining the same collection efficiency. This would improve the sensitivity of the instrument.

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