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Radon Monitoring Using Long-Range Alpha Detector-Based Technology

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Abstract

Long-Range Alpha Detector (LRAD) technology is being studied for monitoring radon gas concentrations. LRAD-based instruments collect and measure the ionization produced in air by alpha decays. These ions can be moved to a collection grid via electrostatic attraction or air currents. LRAD-based instruments using an electrostatic ion-transport design collected approximately 95% of the radon produced ions, while instruments using an airflow transport design collected from 44% to 77% of these ions, depending on detector geometry. The current produced by collecting this ionization is linear with respect to ^{222}Rn concentration over the available test range of 0.07 to 820 pCi/L. In the absence of statistical limitations due to low radon concentrations, the speed of response of LRAD-based instruments is determined by the air exchange rate, and therefore changes in radon concentration can be detected in just a few seconds. Recent tests show that at radon concentrations below 20 pCi/L current pulses produced by individual alpha decays can be counted, thus improving detector sensitivity and stability even further. Because these detectors are simple, rugged, and do not consume much power, they are natural candidates for portable, battery operation.

I. INTRODUCTION

A. Long-Range Alpha Detectors

Monitors based on Long-Range Alpha Detection-technology (LRADs) measure alpha contamination by detecting the ionization that alpha particles create in air [1]. The energy lost by an alpha particle in ionizing an air molecule is approximately 35 eV, so a typical 5.5-MeV alpha decay from ^{222}Rn will produce approximately 157,000 ions. The ionized electron will quickly attach to another air molecule creating an ion pair consisting of two large, charged molecules. These ion pairs can be transported to an electrode where the current produced can be measured. If the alpha decay rate is low enough to preclude pileup, current pulses produced by individual alpha decays can be counted. If the alpha decay rate is too high to resolve individual current pulses, the integrated current at the ion collection electrode is measured. The integrated current measured, or the number of current pulses counted, is directly proportional to the concentration of alpha contamination in the detection volume.

LRADs are classified into two types based on the method used to transport these ions to a collection electrode. Electrostatic LRADs use an electric field to attract ions onto the electrode. Detectors of this type have been successfully used for monitoring flat surfaces such as concrete walls and

floors or for soil surface contamination measurements [2]. Airflow LRADs use air currents to transport ions to the collection electrode. Detectors of this type are useful for monitoring irregularly shaped or metal objects [3].

a. Airflow Design:

b. Electrostatic Design:

Fig. 1: Schematic diagrams of LRADs

Figure 1a is a schematic diagram of a typical airflow LRAD. A set of fans is used to draw air through electrostatic and particulate filters into the detection volume. Ions produced by alpha decays within the detection volume are transported via air currents to the collection electrode, and the current generated is measured using a sensitive electrometer. An electrostatic filter prevents the 10^7 ions/cm³ that are generally present in air from entering the detection volume and biasing the measurement. The particulate filter insures that radon progeny attached to airborne particles do not enter into and decay in the detection volume, creating ions that would bias the measurement.

In Figure 1b the general design of an electrostatic LRAD is shown. Air is drawn into the detection volume via a fan or simply allowed to diffuse through filters into the detector. Radon gas decaying within this volume will produce ions which are attracted to the collection electrodes. The current pulses produced by individual alpha decays can be counted or the total integrated current measured. The statistical nature of detecting 157,000 ion pairs rather than one alpha particle means that LRADs have good detection sensitivity and respond quickly to changes in radon concentration.

B. Sources of Ionization

Ions produced and collected within an LRAD detection volume can be attributed to one of the following sources:

Material Contamination: The material from which an LRAD is constructed will contain some alpha contamination. When contamination located on the inside surface of the detection volume decays, ions will be produced and the overall current will increase. The background signal due to material contamination is typically less than 0.02 femtoamperes (fA) of integrated current [4] or 0.05 counts/minute per liter of detector volume.

Penetrating Radiation: External sources of penetrating radiation, such as cosmic rays, will produce ionization that will add to the overall current measured. However, a minimum ionizing cosmic ray will produce approximately 630 ion pairs per liter of detection volume. Therefore, the integrated current due to cosmic rays is less than 0.1 fA per liter of detector volume. Penetrating radiation will not produce large enough current pulses to contribute to the single-event count rate.

Radon Gas: Because radon is a noble gas it is unaffected by particulate or electrostatic filtering and will enter into the detection volume. Some radon will decay and produce ionization in this volume. The ionization produced by these decays is proportional to the concentration of radon. A radon concentration of 1 pCi/L will produce from 1 to 2 fA of integrated current, depending on detector design and geometry, and 2.2 counts/minute per liter of detector volume.

Radon Progeny: Radon progeny from radon decays inside the detector can plate out on inside surfaces or be swept out of the detector by the airflow. In airflow LRADs most of the progeny are swept out of the detector while in electrostatic LRADs most of the progeny become attached to the inside walls of the detector. In-growth from ^{222}Rn daughters reaches equilibrium in about three hours. Because radon daughters ^{218}Po and ^{214}Po are also alpha emitters, electrostatic LRADs at equilibrium will see three alpha particles for each ^{222}Rn decay within the detection volume.

C. LRAD Radon Monitor Prototypes

Several prototype detectors have been tested both on the bench and in the Radon/Radon Daughter Environmental Chamber (RRDEC) operated by RUST Geotech at the DOE's Grand Junction Projects Office in Colorado. Descriptions of the prototype detectors follow:

HM Detectors: Initial RRDEC tests [5] were conducted using two identical airflow LRADs that were originally designed as personnel Hand Monitors. HMs are rectangular detectors with 23-L detection volumes and a rubberized iris valve on one side for inserting calibration sources or other objects (such as hands) into the detection volume. One HM detector was equipped with an efficient particulate filter while the second was equipped with only a light-duty furnace-type air filter. Filtering is required to prevent radon progeny attached to particulates, such as dust motes, cigarette smoke, or

automobile exhaust, from entering into and possibly decaying in the detection volume.

AM Detectors: A series of detector sub-elements made from 15-cm-diameter tubing were originally designed as personnel Arm Monitors. Ionization collection sub-assemblies can be attached to sample enclosures with detection volumes ranging from 2 to 20 liters. Fans and assorted filter elements can be attached to complete detector configuration. These detectors were used to investigate the speed of response to radon gas and the filtering of radon daughters attached to particulates. Two identical AM detectors were configured with 6-L decay volumes for the second set of RRDEC tests. During this set of tests one AM detector was equipped with a High Efficiency Particulate (HEPA) filter [6] while the second detector did not have a particulate filter. Additional bench tests were conducted with split-fiber filters [7] and impact filters installed on AM detectors. Figure 2 is a schematic diagram and photograph of an AM prototype detector and its sub-elements.

Fig. 2: AM detector prototype

HRM: A Home Radon Monitor prototype detector was constructed from a set of nesting stainless steel camping pans. This detector was used to test the efficiency of electrostatic ion collection and the practicality of using current pulses from individual alpha decays to determine radon concentrations. The simplicity of design and construction inherent in LRAD-technology-based detectors is readily seen in the HRM schematic diagram and photograph shown in Figure 3. This 1.5-L detector is the first in a series of LRAD prototype instruments which will be used to develop continuous radon monitors for home installation. These small, inexpensive, low-maintenance, and battery-operated radon monitors will be patterned after the common smoke detector already found in most homes.

Fig. 3: HRM detector prototype

D. Data Acquisition System

The current generated in an LRAD-technology-based detector from the ionization produced by 1 pCi of radon gas is less than 1 fA. Measurement of such small currents requires a very sensitive electrometer coupled to a detector designed and constructed to eliminate leakage currents. Initial tests were conducted using commercially available Keithley model 617 electrometers. In order to reduce detector cost, size, weight, and power requirements, several generations of LRAD-specific electrometers have been developed. In addition to being small, lightweight, and battery powered, these electrometers provide temperature-compensated mV-level output signals with 0.01% full-scale resolution over jumper-selectable operating ranges from ± 3 to ± 300 pA. Table I lists some relevant parameters for these electrometers.

Table I
LRAD-specific Electrometers

Generation	Size (cc)	Mass (g)	Battery Life	~Cost (\$)
Keithley	10,000	3,600	AC	3,000
1 st	300	342	8 weeks	500
2 nd	200	320	2 years	300
3 rd	25	16	6 years	200

Data acquisition and analysis were done using a personal computer [8]. Electrometer outputs from detectors under test were acquired at 3 to 5 reading/second, and the results were

displayed on the computer screen as a strip chart and optionally recorded to disk. In addition, these raw data were averaged into 1-minute bins and the results displayed and recorded to disk for later analysis.

E. Sources

Several sources were used to test and calibrate LRAD-technology-based detectors. In addition to trips to the RUST Geotech Radon Laboratory mentioned above, a set of NIST-traceable ^{239}Pu surface sources, ranging from 100 to 1100 disintegrations per minute, was employed to establish detector linearity at low activity levels. Uncalibrated sources of ^{222}Rn and ^{220}Rn gas were constructed by enclosing naturally occurring uranium and thorium ores in bottles. Gas from these bottles could then be injected into detectors to study speed of response and radon daughter in-growth.

III. RESULTS

A. Linearity of Detector Response to Radon

Figure 4 shows detector response for both HM and AM airflow LRADs to radon concentrations ranging from 0.06 to 825 pCi/L. For each detector at each point, a 1-hr data set was taken after radioactive equilibrium was reached. The arithmetic means of these 1-hr data sets, minus a constant background due to leakage currents and cosmic rays, are plotted against the RRDEC mean radon concentration as determined by RUST Geotech personnel from the arithmetic mean of 1-hr averages of 10 continuous radon monitors. As can be seen from this plot, LRADs respond linearly, with R^2 s of 0.999 or better, over the entire 4-decade radon concentration test range.

Fig. 4: Airflow LRAD ^{222}Rn Response

B. Ion Collection Efficiency

Table II lists calibration coefficients and ion collection efficiencies extracted from the data plotted above.

Table II
Airflow LRAD Calibrations & Efficiencies

Detector	Volume (L)	Calibration (fA/pCi)	Efficiency (%)
HM-1	23	0.40	44
HM-2	23	0.50	54
AM-1	6	2.43	76
AM-2	6	0.71	77

The HM data listed in Table II are from the first set of measurements taken in the RRDEC. For this set of measurements, detector HM-1 was equipped with an efficient particulate filter while HM-2 was equipped with only a light-duty furnace-type air filter. Therefore, the higher apparent efficiency of detector HM-2 is due to radon progeny attached to particulates that were not captured by the light-duty air filter and that subsequently decayed inside the detector.

The AM data listed in Table II are from the second set of measurements taken in the RRDEC. During this set of measurements, detector AM-1 was not equipped with a particulate filter while AM-2 was equipped with an efficient HEPA filter. Since the calibration coefficients in Table II were determined at approximate radioactive equilibrium, detector AM-1 was measuring ions produced by alpha decays from ^{222}Rn and its daughters ^{218}Po and ^{214}Po . These three alpha decays total approximately 19.2 MeV and will produce about 548,000 ion pairs, leading to a collection efficiency of 76%.

The improvement in ion collection efficiency of the AM detectors as compared to HM detectors can be attributed to better airflow characteristics. Because the HM detectors have rectangular detection volumes, there are corners where the airflow forms eddy currents. Ions become trapped in these eddies and are eventually lost to the metal sides of the detector. The AM detectors have a smooth inner bore that allows laminar airflow, and therefore fewer ions are lost to detector walls.

C. Speed of Response

The speed of response of an airflow LRAD can be seen in Figure 5. This plot shows the current output of an AM detector over a 2-minute time interval. After 15 seconds, a constant amount of ^{220}Rn gas was injected into the air-stream for 60 seconds. This ^{220}Rn gas was generated by pumping air through a bottle containing naturally occurring thorium ore with a constant radon production capacity of approximately 500 pCi/sec. Air flows through the detector at about 6 L/sec, so the radon concentration went from near zero to around 80 pCi/L in about 1 second. Since the transit time for air through the detector is 1 second, each ^{220}Rn decay will be

accompanied by a ^{216}Po decay (0.15-sec half-life) for a total energy release of 13 MeV. The AM detector responds to these changes in radon concentration in less than 5 seconds.

Fig. 5: AM Speed of response to ^{220}Rn Gas

D. Single-Event Alpha Counting

The current output of the HRM detector operating in a 1 pCi/L radon environment over a typical 1 minute time interval is shown in Figure 6.

Fig. 6: HRM Single Event Alpha Current Pulses

The current pulses at time 20 and 40 seconds are due to ions from individual alpha decays reaching the collection electrodes. In a 40-V/cm electrostatic field, all the ions from a single alpha decay arrive at the collection electrodes within a 3-second time interval. A histogram of the total integrated charge per event for the HRM is shown in Figure 7. The

peak from the 5.5-MeV decays of ^{222}Rn is clearly visible. A peak value of 150,000 electric charges corresponds to a collection efficiency of 95%.

Fig. 7: HRM Single-Event Spectrum

For a 1.5-L LRAD operating in radon concentration environments below about 15 pCi/L, the improvement in long-term detection stability achieved by counting current pulses from individual alpha decays instead of measuring the total current can be seen in Figure 8.

Fig. 8: Long-term Stability of Radon Measurement Methods

These measurements were made by injecting approximately 40 pCi/L of ^{222}Rn gas into the HRM. This radon was allowed to slowly diffuse out of the detector while simultaneously measuring both the total integrated current and the number of current pulses produced. After 8 hours the radon reached an equilibrium concentration of approximately

1 pCi/L, which was maintained for several days. Note that the integrated current measurement shows large fluctuations which can be attributed to drifts in the readout electronics zero offset value due to temperature fluctuations. The single-event alpha counting measurement is unaffected by these temperature drifts and remains stable throughout the test period. However, the single-event alpha counting measurement becomes non-linear at radon concentrations above 15 pCi/L, for the 1.5-L HRM detector, due to pileup of the individual pulses. A smaller detector could operate in the single-event alpha counting mode over a larger radon concentration range.

IV. CONCLUSIONS

Long-Range Alpha Detector-based technology shows promise for monitoring radon gas concentrations due to its measurement precision, speed of response to changes in radon concentration, and linearity of response over concentrations ranging from less than 0.1 to greater than 800 pCi/L. Because of the fundamental simplicity of this technology, LRADs are rugged, inexpensive, and can be adapted to portable, battery-powered operation.

By combining and improving the temperature stability of the readout electronics with the single-event alpha counting method at low radon concentrations, a detector capable of high precision radon measurements over a range of concentrations from zero to thousands of pCi/L can be realized. Such a detector could be employed for continuous home radon monitoring.

V. ACKNOWLEDGEMENTS

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- [7] These tests employed 3M Filtrete™ Air Filter Media with densities ranging from 100 to 300 g/m².
- [8] These tests employed Apple Macintosh computers running LabVIEW software from National Instruments.