Title: Alpha Detection on Moving Surfaces

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ABSTRACT

Both environmental restoration (ER) and decontamination and decommissioning (D&D) require characterization of large surface areas (walls, floors, in situ soil, soil and rubble on a conveyor belt, etc.) for radioactive contamination. Many facilities which have processed alpha active material such as plutonium or uranium require effective and efficient characterization for alpha contamination. Traditional methods for alpha surface characterization are limited by the short range and poor penetration of alpha particles. These probes are only sensitive to contamination located directly under the probe. Furthermore, the probe must be held close to the surface to be monitored in order to avoid excessive losses in the ambient air. The combination of proximity and thin detector windows can easily cause instrument damage unless extreme care is taken. The long-range alpha detection (LRAD) system addresses these problems by detecting the ions generated by alpha particles interacting with ambient air rather than the alpha particle directly. Thus, detectors based on LRAD overcome the limitations due to alpha particle range (the ions can travel many meters as opposed to the several-centimeter alpha particle range) and penetrating ability (an LRAD-based detector has no window). Unfortunately, all LRAD-based detectors described previously are static devices, i.e., these detectors cannot be used over surfaces which are continuously moving. In this paper, we report on the first tests of two techniques (the electrostatic ion seal and the gridded electrostatic LRAD detector) which extend the capabilities of LRAD surface monitors to use over moving surfaces. This dynamic surface monitoring system was developed jointly by Los Alamos National Laboratory and at BNFL Instruments. All testing was performed at the BNFL Instruments facility in the UK.

I. INTRODUCTION

Extensive ER and D&D programs, both within the US DOE and at BNFL in the UK, have identified a continuing need for measurement technologies for detecting residual alpha contamination on large surface areas (e.g., walls, floors, in situ soil, or soil and rubble on a conveyor belt). BNFL Instruments, a wholly owned subsidiary of BNFL, has shown that measurement of alpha contamination on surfaces prior to removal from a facility and on loose soil and rubble following removal from the facility would be of considerable benefit for the planning and execution of decommissioning and in evaluating options for and performing subsequent waste disposal.

Building surfaces (walls, floors, etc.) that are not expected to be contaminated but are located in a potentially contaminated area must be treated as potentially contaminated and cannot be reused or disposed of as non-radioactive waste unless the lack of contamination can be positively demonstrated. In addition, decontaminated surfaces cannot be declared nonradioactive until the decontamination is verified. In many locations, if potentially contaminated soil is disturbed, this soil becomes radioactive waste and must be handled and disposed of appropriately. Thus, in situ soil measuring techniques can save time and money during ER operations. If soil and/or rubble is potentially contaminated, disposal costs can be greatly reduced by correctly classifying it and disposing of it, based on the measured (as opposed to assumed or worst case) level of contamination.

Many instruments are available for characterizing gamma contamination on surfaces. However, in situ or fieldable systems for detection of residual amounts of alpha-emitting contamination (such as plutonium-239) on
large, rough, and/or moving surfaces is often difficult, expensive, or impossible by current techniques. The electrostatic LRAD system described in this paper and elsewhere,\textsuperscript{1,3} is ideally suited to measuring contamination on large surfaces. A series of tests, performed both at Los Alamos National Laboratory and at BNFL's Sellafield reprocessing facility in the UK, have demonstrated the sensitivity and operational capabilities of the LRAD-based surface monitors. The results of these static tests are documented in Refs. 4–7.

II. TRADITIONAL METHODS FOR SURFACE MONITORING

Field monitoring of large surface areas for trace amounts of alpha contamination historically has been difficult due to the short range of alpha particles. Traditional alpha detectors are particle detectors in which the alpha particle itself must penetrate the detector. As a typical alpha particle will only travel a few centimeters in air, the detector must be near, or in contact with, the contaminated surface. If the contamination is located on a surface, the alpha monitor must be scanned (usually by hand) over the surface at a distance of a few centimeters. This process works reasonably well with relatively large sources under laboratory conditions where throughput is not an issue. However, this process often breaks down when used to monitor large areas of rough surfaces under field conditions. Traditional fieldable alpha detectors require thin windows which are easily damaged during field operations.

Although traditional techniques can provide useful information about health safety issues caused by isolated spots of contamination, these methods often have difficulty addressing the issue of large surface areas with very small amounts of alpha contamination. When large area surface monitoring is required, at least three techniques have been used.

1. The gamma radiation associated with the primary alpha decay can be monitored using traditional gamma detection techniques. This can be quite effective with uranium and other materials that emit relatively high-energy gamma rays, but it is much more difficult with materials such as plutonium and thorium which emit lower-energy gamma rays.

2. Large areas can be scanned by hand using small, 'health physics type' instruments. Although this technique will locate specific 'hotspots,' it is much less effective for determining average (very low) levels over a large area. In addition, hand scanning is very time-intensive and relatively expensive (both in terms of personnel time and equipment maintenance).

3. Samples of the soil, surface, or rubble can be sent for destructive chemical analysis. This technique provides very accurate analysis of the samples. These samples may or may not be representative of the entire surface. Moreover, sample analysis is costly, time-consuming, and definitely not \textit{in situ}. Increasing the number of samples to increase the confidence in the representativeness of the samples will also increase the time required, expense, and paperwork generated for the sampling.

None of these methods are entirely satisfactory for \textit{in situ}, large-area characterization.

III. LRAD TECHNOLOGY

Detection systems based on the LRAD method are sensitive to the ionized molecules produced by interactions of the alpha particles with ambient air rather than sensing the alpha particles directly as traditional monitors do. The air serves as a "detector gas" that is ionized around the contaminated area by the emitted alpha particles. Typical alpha particles generate about 150,000 electron-positive ion pairs. The electrons quickly attach to a neutral gas molecule, creating a heavy negative ion. Either species of ion can be transported to a detection electrode. The ions create a small current in the electrode. This current is directly proportional to the total number of ions present and hence to the number of alpha particles emitted by the contamination.

The ions are transported to the detection electrode either by an air current (airflow LRAD system) or by a weak electric field (electrostatic LRAD system). The electrostatic LRAD technique is best suited to collecting charge from relatively flat surfaces such as walls, floors, soil, or rubble. Both the static and dynamic LRAD-based surface monitors discussed below utilize the electrostatic LRAD detection system.

Although LRAD-based detector design is discussed in detail in Refs. 1–3, we will mention several significant advantages of LRAD monitors over conventional portable alpha detectors for fieldable surface monitoring applications.

1. Using ambient air as a detection medium means that no bottled gases are required for an LRAD system and that no window is required between the alpha contamination and the detection electrode.

2. All of the ions generated over a large surface can be collected on a single electrode. Thus, a single measurement can respond to the entire contamination loading of a extended area of soil, rubble, or building.
surface. Since the "sensitive element" in the LRAD detector is a simple sheet of metal, the detector can quickly and inexpensively be constructed in any desired shape and size.

(3) Since LRAD-based monitoring systems require no thin windows, fine wires, sensitive crystals, or high voltages; such systems are inherently extremely rugged. Furthermore, the lack of gas-handling systems and complex electronics makes them reliable as well.

(4) The typical sensitivity (in the field) of an LRAD-based monitor is about 2 Bq in less than 1 minute or less than 0.2 Bq/100 cm². This real-time ability is considerably better than the actual field performance of most traditional alpha monitoring systems.

To summarize, LRAD-based monitors are not limited by the range of the alpha particle, but rather by the lifetime of the ions (the observed several second lifetime allows transport of the ions over many meters or tens of meters). The LRAD-based monitors can provide real-time, in situ measurements to aid in operational decisions about surface contamination levels, both in situ and following facility dismantlement.

IV. STATIC LRAD SURFACE MONITORS

All initial implementations of electrostatic LRAD systems have been static. These systems would make a measurement at one location in several minutes or less and then be moved to another spot. Static systems can be used to build up images of large areas in "near-real-time," but the throughput or aerial characterization capability is limited by the detector movement and stabilization times. More details of static surface monitors are contained in Refs. 1 and 8; some results generated by these monitors are included in Refs. 4 and 7.

Since the focus of this paper is moving, or dynamic, LRAD systems, we will only present a brief overview of static operation to contrast with the characteristics of dynamic detectors. The essential components of a simple static electrostatic LRAD monitor are shown in Fig. 1.

Ions generated over the surface to be monitored are collected on the detection electrode by a bias voltage (generated by the bias battery). This flow of ions represents a small current which can be detected by a current meter or recording device. This current is proportional to the total amount of contamination on the surface covered by the enclosure. The detector enclosure serves two purposes; first, to define the active area of the detector; and second, to prevent externally generated ions from reaching the detector electrode and causing a spurious current.

V. DYNAMIC LRAD SURFACE MONITORS

Both of the limitations mentioned above that limit LRAD surface detection to static applications can be addressed by adding additional electrodes to the simple implementation shown in Fig. 1. Externally generated ions can be excluded from the LRAD chamber using an electrostatic electrode as illustrated in Fig. 2. An electric field between the guard electrode and the surface to be monitored will exclude the unwanted ions from the LRAD enclosure. Inclusion of the guard electrode (with an applied guard voltage) removes the requirement for physical contact between the enclosure and the surface.
The noise current \( I_{\text{Noise}} \) caused by capacitive coupling between the detection electrode and the surface to be monitored is given by

\[
I_{\text{Noise}} = C_{ds} \frac{dV_b}{dt} + V_b \frac{dC_{ds}}{dt},
\]

where \( C_{ds} \) is the capacitance between the detection electrode and the surface to be monitored and \( V_b \) is the bias voltage. If \( V_b \) is assumed to be constant then Eqn. 1 reduces to

\[
I_{\text{Noise}} = V_b \frac{dC_{ds}}{dt}.
\]

If a grid electrode is introduced between the detection electrode and the surface to be monitored as shown in Fig. 3, the motionally induced noise current becomes

\[
I_{\text{Noise}} = V_b \frac{dC_{gs}}{dt},
\]

where \( C_{gs} \) is the capacitance between the detection and grid electrodes. Notice that the noise current is now decoupled from the surface to be monitored and depends only on the interelectrode capacitance within the detector. The interelectrode distance (and hence changes in interelectrode capacitance) can be mechanically controlled, even if the detector is moving, eliminating this source of noise. Thus, noise caused by motion of the detector relative to the surface to be monitored can be reduced or eliminated by use of the grid electrode as shown in Fig. 3. Note that both electrical and mechanical noise contributions can be analyzed using Eqn. 1.

The guard electrode and the gridded detector concepts are combined in the large dynamic surface monitor. This detector system can be continuously moved relative to the surface to be monitored with little or no loss of sensitivity. Movement of the detector relative to the surface includes both “moving-LRAD” applications (e.g., in situ wall, floor, and soil characterization) as well as “moving-surface” applications (e.g., soil and/or rubble conveyor belt systems). Although the grid on the front of the detection chamber is certainly more “delicate” than no electrode at all, the grid does not have to be made from a thin or easily breakable material. Grid wires as large as 0.5 mm in diameter have been demonstrated and there is no reason to believe that larger wires would not work as well. The current supplied to the exposed guard electrodes can be limited to less than a microAmp without affecting the operation of the electrode. Thus, no additional safety hazard is introduced in the dynamic system.
VI. TEST RESULTS

The guard-electrode and gridded-detector concepts have been tested individually. In both cases, small, calibrated americium-241 alpha sources were used to monitor the detector response. These sources were on the form of electroplated metal disks with an active surface diameter of about 2.5 cm.

The errors associated with both signal and background measurements are indicative of the measured standard deviation of the distribution. As all of these data sets represent the average of 50 samples (each sample taking approximately 1 second), the standard deviation of the mean is approximately \( \sqrt{50} \), or about 7 times smaller. Thus, the mean values of the raw data given are known seven times better than the measured errors indicate. That is, for quantities which depend on the uncertainty of a measurement,

\[
\sigma_{\text{mean}} = \frac{\sigma_{\text{distribution}}}{\sqrt{n}},
\]

where \( n \) is the number of (uncorrelated) samples.

The limit of detection (LoD) is defined as the smallest signal that can be detected above background with 3\( \sigma \) confidence. If the standard deviation in a very small signal (\( \sigma_S \)) is approximately equal to the standard deviation of the background (\( \sigma_B \)), then the standard deviation in \( S - B \) is approximately given by

\[
\sigma_{(S-B)} = \sqrt{2} \sigma_B,
\]

so the LoD for an LRAD-based detector system is defined by

\[
\text{LoD} = 3\sqrt{2} \frac{\sigma_B}{\text{Eff}}.
\]

For the data presented in this paper, \( \sigma_B \) is measured in mV and Eff in mV/Bq, so LoD is specified in Bq.

A. Guard Electrode Results

Initial tests were performed with the detector resting on the grounded surface. The efficiency of the LRAD detector (Eff) is defined as

\[
\text{Eff} = \left( \frac{S - B}{N} \right),
\]

where \( S \) is the measured response of the detector to a source of strength \( N \) and \( B \) is the response of the detector with no source present.

A 180-Bq Am-241 source was placed approximately in the center of the region under the detector. The response to background and source were, respectively, \( B = -43.4 \pm 2.8 \) mV and \( S = 161.6 \pm 19.0 \) mV. The sensitivity of the current monitor had been set so that \( 1 \) mV \( \approx 10 \) fA; thus the efficiency of the detector is

\[
\text{Eff} = \left( \frac{161.6 + 43.4}{180} \right) = 1.13 \text{mV/Bq} \approx 11.3 \text{fA/Bq}.
\]

This efficiency is consistent with earlier measurements.\(^{13}\) In addition, the individual values for \( S, \sigma_s, \) and \( \sigma_B \) are also consistent with those measured earlier. Substituting this measured efficiency into Eqn. 6, the LoD for this detector becomes

\[
\text{LoD} = 3.75\sigma_B.
\]

As described in Eqn. 4, \( \sigma_B \) can be reduced by increasing the measurement time (up to the limit where statistical noise no longer dominates \( \sigma_B \)).

A 0.5-m by 0.5-m electrostatic LRAD surface monitor was fitted with a guard electrode as illustrated in Fig. 2. The guard electrode was an 8-cm-wide copper foil which extended all the way around the detector enclosure. For these tests, a (semi-) reproducible source of ions was generated using a heat gun waved in front of the gap between the detector and the surface to monitored. In the short term it proved possible to maintain a fairly constant distance and rate of motion so that the number of ions was relatively consistent. As the long-term reproducibility of this ion generation technique is quite poor, each data set was taken in a consecutive series of measurements.

Following calibration and stabilization, the data illustrated in Fig. 4 were obtained with a gap between the enclosure and the surface of 30-mm and the heat gun (a source of copious ions) waved about 10 cm away from the gap. The LoD was calculated from the raw results using the relationship derived in Eqn. 9 for a single (1-second) sample. Thus, the graphical result indicates the smallest source that could be reliably detected (in one second) as a function of guard voltage. Application of the guard voltage can reduce the noise current by a factor of about 85.

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Fig. 4. Limit of detection (LoD) as a function of guard voltage for a detector-to-surface gap of 30 mm. As described in the text, these data represent the LoD for a 1-second measurement time. The LoD can be reduced by increasing the measurement time. The ultimate LoD (for seal voltages greater than about 150 V) is 15 Bq.

The set of data illustrated in Fig. 5 was obtained in the same manner as that shown in Fig. 4 but with a detector-to-surface gap of 105 mm and the heat gun waved about 15 cm away from the gap. Application of the guard voltage can reduce the noise current by a factor of about 80.

The application of a guard voltage can successfully reduce the infiltration of externally generated ions through a detector-to-surface gap as large as 105 mm. The ultimate LoDs achieved for both gaps are consistent with the ‘no-gap’ LoD. Thus, these tests did not fully stress the guard electrode concept; the LoD reduction is greater than a factor of 80.

B. Gridded-Detector Results

A 0.5-m by 0.5-m electrostatic LRAD surface monitor was fitted with a grid electrode as illustrated in Fig. 3. The grid was formed of galvanized steel wire mesh with a grid spacing of 1 cm and a wire diameter of approximately 0.5 mm. For all of the gridded detector tests, one side of the ground plate (surface to be monitored) was moved at approximately the speed shown. Thus (as with the guard electrode results), the grid results shown in this paper must be interpreted as qualitative indications rather than actual quantitative measurements of effects.

Grid electrode measurements were obtained with an detector-to-surface gap of 55 mm, a 1-cm wire mesh grid connected the LRAD enclosure, and the grid/enclosure grounded. As a relatively severe test of the grid electrode, one side of the ground plate was moved at ± 20 mm in each second.

With the wire grid in place and no surface motion, the detector results for a 338-Bq alpha source is $B = -17.4 \pm 3.6 \text{ mV}$ and $S = 191.8 \pm 34.4 \text{ mV}$. Thus, for the gridded detector, the calculated efficiency and LoD are

$$Eff = 0.62 \text{ (mV/Bq)} = 6.2 \text{ (fA/Bq)}, \text{ and}$$

$$LoD = 24.5 \text{ Bq}.$$

(10)

The data illustrated in Fig. 6 illustrate the results of moving one side of the ground plate through ± 20 mm under the gridded detector. In this case, the measured uncertainty is ± 36.9 mV, corresponding to an LoD of 245 Bq in 1 second. The results in this figure (as well as Fig. 7) are expressed in terms of “equivalent alpha response (Bq).” The equivalent alpha response (EAR) is the strength of alpha source which would be required to produce the observed electrical signal. Thus,

$$EAR (\text{Bq}) = \frac{\text{Measured Current (fA)}}{Eff (\text{fA/Bq})}.$$

(11)

Expressing noise signals in EAR gives an indication of the magnitude of alpha contamination which would be obscured by the noise.
Following these tests, the grid was removed and identical calibration tests were performed (again with a 338-Bq alpha source and no surface movement) with the results $B = -15.6 \pm 6.2$ mV and $S = 334.3 \pm 19.2$ mV. Thus, the calculated efficiency and LoD for the ungridded LRAD are

$$Eff = 1.03 \text{ (mV/Bq)} = 10.3 \text{ (fA/Bq)}, \text{ and } LoD = 25.4 \text{ Bq.} \quad (12)$$

Notice that although the background noise is larger in the ungridded detector, the ungridded efficiency is similarly greater so the LoD remains the same.

The data illustrated in Fig. 7 show the result of moving one side of the ground plate through $\pm 20$ mm under the ungridded detector. The measured uncertainty is $\pm 2448.2$ mV, corresponding to an LoD of 10,032 Bq. However, the saturation point of the electrometer is between 2.5 and 3 V. At this efficiency (~1 mV per Bq), this corresponds to between 2500 and 3000 Bq. Thus, the electrometer was often saturating in this data set; the "real" LoD is probably larger.

VII. CONCLUSIONS

Both the guard electrode and the grid electrode are effective for removing/preventing spurious current noise associated with noncontact (enclosure-to-surface) operation of LRAD-based detectors. In particular,

1. Very large numbers of ions generated outside the chamber can be effectively prevented from entering the chamber by an electric field generated by a guard electrode. An 8-cm-wide sealing electrode can operate effectively with gaps as large as 105 mm.
2. The LoD is not affected by the presence of a grid or seal electrode.
3. A 1-cm wire mesh grid reduces the motionally induced noise signal by a factor of at least 40.
4. An 8-cm-wide guard electrode reduces the infiltration of externally generated ions by a factor of at least 80.

All of the results contained in this paper are somewhat qualitative. Hence, these results cannot be used to design a dynamic electrostatic LRAD monitor; but the results do indicate that both guard electrodes and grid electrode can should be used in the design of a dynamic monitor. These two developments (guard and grid) will enable the construction of dynamic LRAD detectors for use over moving surfaces such as soil, building surfaces, and rubble.
NOMENCLATURE

\[ B = \text{the mean background}, \]
\[ \sigma_B = \text{the standard deviation of the background}, \]
\[ S = \text{the mean response to a source (including background)} \]
\[ \sigma_S = \text{the standard deviation associated with } S, \]
\[ N = \text{alpha source strength in Bq} \]

\[ Eff = \frac{(S - B)}{N} \quad \text{efficiency of detector} \]

\[ LoD = 3\sqrt{2} \frac{\sigma_B}{Eff} \quad \text{limit of detection.} \]

REFERENCES


