AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as worked performed under the auspices of the U.S. Department of Energy.

MASTER

Form No. 836 R5
ST 2629 10/91

Title: Alpha Detection as a Probe for Counter Proliferation

Author(s): J. E. Koster, J. P. Johnson, D. W. MacArthur, and
S. G. Walters

Submitted to: IEEE International Carnahan Conference on Security Technology
Albuquerque, NM, Oct. 12-14, 1994

Alpha Detection as a Probe for Counter Proliferation

J. E. Koster, J. P. Johnson, D. W. MacArthur, and S. G. Walters

Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract --- An indication of the presence of special nuclear material (SNM) can be obtained by the detection of alpha particles from the decay of the SNM. Current techniques for detecting alpha particles have a number of limitations. Sensitive conventional detection of SNM traces involves off-site laboratory analysis - but at the loss of an on-site confirmation. Fieldable detection instruments, on the other hand, are delicate and have poor sensitivity. New long-range alpha detection (LRAD) technology mitigates these limitations. An LRAD-based instrument relies on the detection of the hundreds of thousands of ions produced in ambient air by one emitted alpha particle. The ions can be transported to an ion detector at a distance much greater than the range of the original alpha particle. The LRAD-based monitors have the characteristics of high sensitivity, fast (real-time) response, ruggedness, and reliability. Many of the designs are quite portable. In this paper, several scenarios are identified for which particular LRAD-based detectors can provide confirmation of proliferation activity.

INTRODUCTION

Sensitive detection of alpha particles in the field could provide a useful tool in safeguards and nonproliferation efforts. A signature of nuclear activities is the alpha decay of uranium, plutonium, or other transuranic nuclear material. This material might be in the form of residues or of effluents and could easily be overlooked by the creators of the material. The two traditional methods of detection are either sensitive or real-time - but not both. The more sensitive method is to obtain samples for later analysis. Often, this analysis is actually the detection of characteristic gamma rays rather than alpha particles. Under potentially adverse field conditions there is a high possibility of mixing up the samples with respect to either locations or the reasons for suspicion. Moreover, the delay in obtaining results provides time to the suspects for concealment of activities or for escape. Real-time monitoring for alpha particles in the field has traditionally been limited by the short range of the alpha particles in air, the relative insensitivity of fieldable alpha monitors, and the delicate nature of the laboratory instruments. To be effective, such detectors must be held within a few centimeters of - or in contact with - the source of the alpha particles. This is necessary because the alpha particles do not penetrate far in air. If the surface being monitored is large or complex, traditional monitoring is difficult or impossible. For a large surface in which contamination might be spread over a large area, the small active area of a fieldable monitor is limited to detecting a small fraction of decays. For a complex surface with inner faces, holes, grooves, or cracks, the alpha particles cannot reach the exterior surface and hence the traditional detector. For any surface, the farther away the sensor is held, the less the

energy of the alpha particle because the particle loses energy quickly in air. Moreover, the alpha particle must also penetrate a thin window to enter the detection chamber of conventional detectors. Two consequences result from this. The effective energy threshold of a conventional detector depends upon the manner in which the detector is operated. Also, a trade-off exists between getting the sensor close to the surface being monitored, and puncturing the delicate window.

Long-range alpha detection technology

Long-range alpha detection (LRAD) technology consists of detecting the ions produced in air by the ionizing alpha particles instead of detecting the alpha particles directly. Alpha particles produced in the decay of the nuclear material of interest typically have energies of approximately 5 MeV. The energy lost by an alpha particle in ionizing an air molecule (generally N_2 or O_2) to produce an ion pair is approximately 35 eV. Therefore a typical alpha particle produces over 140,000 ion pairs. The ionized electron normally attaches quickly to another air molecule and so an ion pair consists of two large, charged molecules. The ion pairs can be transported to an ionization chamber consisting essentially of two electrodes (Fig. 1).

Fig. 1. Long-range alpha detection via the ions produced in air.

Two important limitations of traditional fieldable detectors are thereby mitigated with LRAD: range and sensitivity. LRAD is limited by the range over which the ions can be transported (tens of meters) rather than the range of the alpha particles (a few centimeters). Ion range is determined by the probability of recombination of ions with other air molecules or nearby surfaces. Thus range depends weakly on air pressure

and more importantly on the geometry of the detection situation. For example, the measured lifetime for ions in a 3.2-cm diameter pipe is 5 seconds (Fig. 2). The range depends on the speed at which the ions can be transported. In this case the lifetime was measured at air flows of 97.5 cm/s for distances up to 2.43 m [1]. LRAD is sensitive to the 140,000 ion pairs produced instead of one alpha particle. This charge amplification of 140,000 to 1 generally implies a better signal-to-noise ratio. Moreover while a fraction of an alpha particle cannot be detected, a fraction of the 140,000 ion pairs can be. Such a fraction would represent an alpha particle that has lost some energy (and may be below the threshold of a traditional detector) or would represent detection at a great distance - following recombination of some of the ion pairs.

Fig. 2. Detector response as a function of distance in a 3.2-cm diameter aluminum pipe. The airflow rate was 97.5 cm/s so the lifetime of the ions in the pipe is 5.2 ± 2 s.

LRAD technology is also an improvement over traditional detection in other ways. The electrodes comprising the ion detector can be virtually any size and can be sturdy. The signal processing consists of a small electrometer for measuring the DC current produced by the ions. Thus an LRAD itself can be very rugged and yet (with some trade-off) portable.

The LRAD technology considered in this paper involves only a continuous measurement of DC levels of current. The statistical nature of detecting 140,000 ion pairs rather than one alpha particle means that the response time of an LRAD is very quick - in some applications less than a few seconds. Because of the integration inherent in the detection process itself, signal processing is simplified and an LRAD is easily automated. In contrast, a traditional field monitor has to integrate its single pulses over time in order to produce an activity level and then perhaps trip alarms or broadcast alarms or levels. Thus an LRAD has a simpler, more robust electronics package. (Different realizations of LRAD technology may be developed; see ref. [2]).

The characteristics of an LRAD of long range, quick response, ruggedness, and simplified electronics make for an alpha detector that is easier to operate - and less operator dependent - than a traditional field monitor.

The technology of detecting air ions applies to situations in which the ionizing particles are things other than alpha

particles. Alpha particles are preferentially detected, however, since beta, gamma, and neutron radiation deposit less energy per unit distance in air per unit incident energy. Nevertheless, in this paper applications are identified for which the signature is the presence of beta particles (electrons) or gamma rays.

Ion transport

Two methods have been developed for transporting the ions from the path of the alpha particle to an ion detector. Fig. 3 is a schematic of an LRAD utilizing the flow of air.

Fig. 3. Schematic of an airflow LRAD in an object monitor configuration. Filtered ambient air is drawn over the object to be monitored (not pictured) by the fans. The ions produced by emitted alpha particles are collected on the first grid, and the current created by the ions is read out by an electrometer.

The air passes through a particulate filter which removes large particles and decouples air currents inside the LRAD from air currents outside. The air passes through a simple electrostatic filter which removes any ions already present. The filtered air that flows uniformly through the chamber collects any ions generated by sources of alpha particles within the chamber. The ion pairs are transported in the air current into the volume between the first (signal) electrode and the second (high-voltage) electrode. Because air must flow through the ion detector, these electrodes are in the form of wire mesh or grids. The bias voltage applied by the battery attracts one polarity of ion to the high-voltage (HV) grid and the ion of opposite polarity to the signal grid. The flow of these ions to the case of the enclosure is measured by a sensitive electrometer. A manifold of fans draws the air through the chamber. The fan manifold is preceded by a baffle which reduces backstreaming of air past the fans into the chamber. For particulate filtering, a high-efficiency particulate air filter (HEPA) is very effective. Various baffles have been tried with some success as well. In connecting a bias voltage, either polarity works equally well. Fig. 3 shows a positive bias that will attract the negative ions

and force the positive ions onto the signal grid. This LRAD detects only one polarity of ions, although both are present. (See ref. [3].)

The airflow approach works well on objects with complex shapes for which air flowing around (and within, as the case may be) the object collects ions produced by alpha particles emanating from any surface - including interior surfaces and the inside of cracks. Airflow LRADs can also be adapted for applications in which the object under study forms the enclosure; for example, the inner surface of pipes and ducts.

The alternative method of ion transport consists of an electrostatic field permeating the active volume of the detector. A large potential applied to the signal electrode (as depicted in Fig. 4) attracts ions of one polarity to the signal electrode. The effect is similar to what occurs in the collection volume of an airflow LRAD (Fig. 3); however, the entire chamber serves as a collection volume due to the larger bias voltage. The electrostatic field within the chamber acts to separate the ion pairs immediately, reducing the amount of recombination. Therefore an electrostatic LRAD is often more efficient than an airflow LRAD. The electrostatic design is most appropriate when monitoring flat surfaces such as soils. The signal electrode can be brought close to - and equidistant from - the surface (Fig. 4). No air flow is present to disturb any loose sediment on the surface. In practice, a perfect air seal is not required, but externally-induced air currents must be eliminated in order to eliminate the 10^7 ions/cm² typically carried in ambient air. As with airflow LRADs, both polarities of bias voltage on the electrodes work equally well. Because the input-offset voltage of the electrometer is small, the entire battery voltage is applied to the signal electrode as well as the bias electrode. The electrometer must be capable of "floating" operation with neither input nor output connected to ground, but otherwise it is similar to that used in an airflow LRAD. The electrode in an electrostatic LRAD is normally a solid plate as there is no air flow necessary. (See ref. [4].)

Fig. 4. An electrostatic LRAD as a (soil) surface monitor. No airflow is required in this LRAD. The ions produced by emitted alpha particles are electrostatically attracted to the signal plane. The ion current is read out by the electrometer. The guard plane reduces leakage currents through the electrometer by a factor greater than 10^5 .

ON-SITE INSPECTIONS

The search parameters in an on-site inspection can vary. The inspection might be a single challenge inspection, or perhaps clandestine. The inspection might be an initial inspection to establish baselines for sensitive parameters. The

inspection might be a follow-up in which deviations from baseline are sought for sensitive parameters. The site itself might be an operating enrichment, reactor, reprocessing, or storage facility. The site may be a facility that has been declared shut-down. Or it might be barren desert, indicated by intelligence or document review.

For a challenge inspection, emphasis is on measuring a parameter which is clearly greater in value than would be normally expected. The technology must be capable of high sensitivity and short-term precision so that any positive measurement deviates from the norm with large confidence. A sound understanding of possible backgrounds is necessary.

An initial inspection to establish baselines is frequently made slowly, with great deliberation, in order to determine present values of parameters within a narrow range. High sensitivity is thus important, enabling a better determination in a shorter time.

For later inspections, emphasis is on detecting a deviation from baseline for a given parameter. Long-term reproducibility is very important. The likely target is a facility which has been declared closed, for which evidence of recent operation is sought.

Depending on the facility, special nuclear material may be normally present. Enrichment, reactor, and reprocessing facilities may be expected in peaceful uses of nuclear energy. Suspicious activity consists of high levels of uranium enrichment, or plutonium processing.

In general, the advantages of LRAD monitors in on-site inspections are their sensitivity, ruggedness, and portability. The sensitivity implies that these monitors are useful in all the types of inspection identified above. The usefulness might be limited in specific applications by two issues. For challenge inspections, the contribution to a signal from non-suspect background might be difficult to ascertain without having a controlled background measurement. For both challenge and return inspections, a background signal which varies over time and is not well-characterized also adds uncertainty to the measurement of alpha activity. Finally, for return inspections the response of the monitor to uncontrolled components of the signal which can vary over long intervals must be understood. For example, the monitor response may be different upon a repeat inspection due to a different moisture content in the air or in the soil. These issues will be addressed for the specific applications below.

Soil surface monitoring

Soil contamination is possible at any site where nuclear material has been (or is being) mined, processed, or machined. Older sites are often more contaminated because less emphasis on contamination control existed and because such activities could have occurred over a longer time period. However, newer sites may be highly contaminated if speed of process, or volume of material handled, was paramount. If the contamination level is high, it can be detected with conventional alpha particle monitors. Detecting lower levels of contamination (as might be encountered if the facility tries to either remediate contamination or hide its activities) is more difficult. A typical environmental contamination involves a large area (acres) that is contaminated at a level (10 to 100 pCi/g) only slightly above natural backgrounds. The

contamination of soils by SNM in a proliferant country is likely to occur around processing plants. Also, hadrodynamic test sites (suspected or declared) normally have some contamination dispersed around the firing pads. Sites where no apparent facilities exist can also be monitored. Normally such sites would be suspected on the basis of intelligence or documentation, perhaps as sites of buried material.

LRAD technology is uniquely suited to measuring alpha contamination over large areas. The electrostatic LRAD monitor (Fig. 4) is used for field monitoring of soils. Such a detector is an open-bottomed box that is placed face down on the soil to be monitored. This design is more efficient at monitoring flat surfaces than an airflow LRAD monitor because the distance from surface to detector electrode is short and uniform across the surface. In addition, an electrostatic LRAD monitor has lower power requirements (no fans) and is more rugged. These capabilities are evinced by the three LRAD monitors already constructed and operated for environmental remediation projects. Two 1-m by 1-m by 20.3-cm soil surface monitors, each weighing about 136 kg, are mounted on the front loaders of separate small farm tractors. Currently, each tractor is operated only to move its detector and does not run while measurements are being taken. A smaller 0.5-m by 0.5-m by 15.25-cm monitor is mounted on a dolly. For either size of detector, the data acquisition electronics are left attached and running and so the set-up time consists of positioning the monitor at either a suspect location or at a point on a pre-established survey grid. Data collection times vary from 5 to 15 minutes at each location, depending on the sensitivity desired. A background reading is obtained by taking a measurement with the monitor placed on a thin aluminum plate. This background is due to the normal LRAD backgrounds from cosmic ray penetration of the monitor, leakage currents, and electronic noise. The background reading is subtracted from the soil readings.

An entire LRAD monitor, including data acquisition and display computer, is powered in the field by its own automotive battery and DC-to-AC converter. Each tractor can be stored and transported in a trailer outfitted with minor modifications to handle this task.

Note that the LRAD monitor is insensitive to contamination outside the monitor. Therefore, if complete coverage of an area is desired, the spacing of grid points must be equal to the dimensions of the opening of the monitor (its footprint).

It must be kept in mind that an LRAD soil surface monitor measures only alpha-emitting contamination in the surface layer of the soil, because the alpha particles must penetrate any overhead soil and then produce ion pairs in the air. This penetrable depth of soil is approximately 36 μm for typical alpha particles of about 5 MeV, but the depth depends somewhat on the composition and porosity of the soil being monitored. For example, an extreme case is the monitoring of sand. Fig. 5 shows the response of a small soil-surface monitor to soil moisture content. Clearly, sensitivity is reduced when monitoring wet ground. In addition, vegetation can interfere with measurements by either short-circuiting the electrodes or blocking the alpha particles emitted from the soil surface. For dealing with vegetation, a weed-eater can accompany the soil monitor and be utilized to crop the grass and weeds.

Fig. 5. Response of a surface monitor to soil as a function of the moisture content in the soil.

All the soil surface monitors operate with a 300 V bias. This voltage is chosen to balance the plateauing of the detector response (Fig. 6) with the need to supply the voltage with small, stable, long-lived batteries. A reading of one femtoampere (10^{-15} A, or 1 fA) corresponds to 6 disintegrations per minute (dpm) of ^{239}Pu , as determined by National Institute of Standards and Technology (NIST)-traceable sources. For other alpha emitters the monitors have a response which varies as the average energy of the alpha particle. Linearity of the response has been measured from 100 dpm to 300,000 dpm and is excellent. The guard plane (Fig. 4) reduces leakage currents through the electrometer by a factor of at least 10^5 .

Fig. 6. Large soil surface LRAD monitor response. The electrometer current is measured for different bias voltages on the electrodes. The alpha particle source is a 224,000 disintegrations per minute ^{238}Pu . Only a small gain in current is obtained by utilizing voltages greater than 300 V.

The response in fA is more directly converted to roentgen per unit time because the fA measurement is related to the rate of ion production when the ion collection efficiency is known. Contamination levels are discussed in U.S. Department of Energy (DOE) regulations in units of dpm/100 cm² and therefore results from LRAD surface monitors are reported in such units. It is possible to report activity in units such as pCi/g if assumptions are made about alpha particle range in soil and soil density.

Reproducibility in repeated readings of an LRAD soil surface monitor at the same location is 5% to 10%, depending largely on ground moisture (such as morning dew). Another cause for variation - which is under operator control - is the degree of sealing between detector and ground.

Existing LRAD soil surface monitors have been operated in the field. Six locations at three technical areas of Los Alamos National Laboratory have been characterized with an LRAD monitor. Two sites at Kirtland AFB, Albuquerque, New Mexico have been monitored for Sandia National Laboratory. LRAD monitors have participated twice at the Uranium in Soils Integrated Demonstrations at the Fernald Environmental Management project in Ohio. Calibration pads in Grand Junction, Colorado and Grants, New Mexico have been monitored.

The measurement with the tractor-mounted LRAD surface monitor at Kirtland AFB [5] was cross-checked by a GeoTech team using a (NaI) scintillometer. Data were taken at the same grid points for each detector. The LRAD monitor averaged over a one-meter square area at each point, while the scintillometer averaged over approximately 2.3 m² with decreasing sensitivity away from the small scintillometer. A comparison of the two readings using the same graphics software is shown in Fig. 7. Elevation contour lines are shown at 1.5-meter intervals. Shading denotes activity levels. The general trends as interpolated between grid points are the same for the two technologies. The average levels of contamination are at background level. Both detectors gave high readings in the northeast corner.

The comparison of the two technologies was also done for 10 "hot spots" within the test area. Results for the hot spots are not included in Fig. 7. Small point sources of contamination comprising these hot spots are not as well determined in terms of absolute activity with the LRAD surface monitor, because the LRAD monitor includes the surrounding square meter of less contaminated ground. The strength of LRAD technology is in monitoring wide-spread low-level contamination. However, a trade-off is certainly possible in terms of size because an LRAD surface monitor with a smaller footprint would give a better reading at a hot spot but would have to be moved several times in order to measure over a large area.

Soil surface monitors have been used at two locations at Fernald in 1992. The monitors will be used again at Fernald in June of 1994, for which it is planned to make a comparison with some other technology that monitors surface contamination.

Fig. 7. Comparison of LRAD and scintillometer measurements. Data points are taken on 96 points on a square grid. Interpolation is performed between grid points in order to produce the shaded areas corresponding to ranges of response for the respective detectors. LRAD data is measured over 1 square meter.

Concrete/asphalt surface monitoring

For monitoring blasting pads or other small floor areas at facilities in (possibly) proliferant countries, a smaller LRAD monitor is very useful. The dolly-mounted surface monitor has been fielded at a blasting pad at Los Alamos National Laboratory and on calibration pads at Grand Junction and Grants. The calibration pads consist of cement mixed with known amounts of radioisotopes. The blasting pad is an old asphalt pad left from the Manhattan Project. The LRAD data were taken on the staggered grid points shown in Fig. 8. The grid points are at intervals of 3 and 1.5 meters. Interpolation with the graphics software is again used in generating the shaded areas. (The rectangle at the middle of the left side represents a concrete pit.) For comparison, at the hotter spots indicated by the LRAD surface monitor a hand-held Ludlum 139 alpha survey meter was used. In Fig. 8, the Ludlum data are shown at the proper locations in terms of boxed numbers representing counts per minute. Due to its low response rate and small monitoring area (4.4-cm by 17.8-cm) it is difficult to calibrate the Ludlum against the LRAD. However, relative

response over the locations measured is similar for the two technologies. Both technologies find two spots on the pad which are above background levels.

Fig. 8. Comparison of small surface LRAD monitor with spot results from a conventional hand-held survey meter. Results obtained on an old blasting pad at Los Alamos National Laboratory.

Large area monitoring for inspections

Both the large tractor-mounted LRAD surface monitor and the smaller dolly-mounted LRAD surface monitor can be fielded for on-site inspections. Both versions of monitor are completely self-contained - however, the larger monitor would require more effort in terms of transporting the tractor into areas of interest. A 1-m by 1-m monitor could be operated by two people (mostly because a second person is helpful in placing the monitor).

At 15 minutes per position, an area of 160 m² could be monitored with 100% coverage in one week. More practical is to accept less coverage: for example, with grid points spaced five times the footprint size - i.e. every 15 meters - 36000 m² could be monitored (with 0.4% coverage). An LRAD surface monitor mounted on a dolly can be maneuvered and operated by one person. With a 0.5-m by 0.5-m footprint, it could monitor a 3-m by 4-m room or blasting pad with 100%

coverage in a day, given 10 minutes at each position. If less coverage, or a reduced confidence level, was acceptable this time could be reduced. For either monitor, battery life for biasing the electrodes with standard off-the-shell dry cells is about 1 year. The lap-top computers and commercial electrometers currently used with these monitors are powered by an automotive battery which lasts 24 hours between recharges.

Hand-held surface monitor

There are numerous scenarios in which only a small surface area needs to be examined for traces of nuclear material. These scenarios include more than just testing a patch of soil: spot checking a firing pad, a loading dock, a tabletop, a floor in a room, even a portion of a wall. The surface of a storage container or barrel might be of interest. A portable, hand-held version of the tractor-mounted surface monitor would suffice in each of these scenarios. An alpha contamination monitor lightweight enough to be carried around yet sensitive would address these scenarios.

A small monitor analogous to the tractor-mounted large soil surface monitors has been prototyped. This electrostatic monitor has a footprint of about 1/2-m by 1/4-m and a weight of about 5 kg. In addition to the standard laboratory testing with plutonium sources, the prototype hand-held monitor has been tested in the field at calibrated pads at Grants, NM, and at a Decommissioning and Decontamination project at Los Alamos National Laboratory.

Advantages of an LRAD-based surface monitor for checking walls or floors (or ceilings) is that the alpha-emitting contamination might itself reside in cracks in the material. The alpha particles may not get beyond the surface in such cases, yet the electrostatic field of an LRAD-based monitor can pull the air ions onto the collection plate of the monitor. A coating of paint might hide the contamination - unless the paint is chipped or peeling.

Issues identified in case an optimized monitor is developed involve making the monitor lightweight yet sufficiently sturdy to avoid flexion of the chamber during use. Additionally, the air seal and the electrical grounding must be adequate for such a lightweight instrument. If the surface is a poor conductor, the prototype LRAD monitor can be affected by capacitive coupling to the outside of the monitor. It is possible to alleviate this problem. Lastly, the measurement and display of the ion current must be portable and user-friendly.

Sample monitoring

There are scenarios in which the SNM content in soil is of interest yet a soil surface monitor is difficult to use. For example, the proliferants may be suspected of covering over a potentially contaminated site with fresh soil. This is one possible reason for the need to monitor soil that is below the surface. Another scenario is the desire to monitor soil on a rutted surface - for example near the bottom of a small trench which contains, perhaps, a leaky pipe. In either of these scenarios it is possible to scoop up a soil sample.

Alternatively, whether for reasons of environmental conditions or hostility, the need may be to obtain a soil sample - even from the surface - and leave the vicinity very quickly.

These scenarios require a detector which can monitor a sample of soil. The LRAD technique is applicable in the form of a closed chamber. Sensitivity is even better than for a soil surface monitor because of typically smaller volume and total control over sealing off the enclosure from ambient air currents. The soil sample is spread out thinly on a shallow stainless steel tray and slid through a door into the detector chamber (Fig. 9). The door has a rubber seal. Ion transport is established with an electrostatic design, as for the soil surface monitors. Such a monitor is useful as a screening device because of its great sensitivity; however, at present it cannot determine isotopes of the SNM contamination.

Fig. 9. Sample monitor. A shallow tray of soil or water is placed in the bottom of the enclosed chamber. The chamber door provides a seal. An electrostatic field transports ions to the electrodes from alpha particles near the tray.

A prototype LRAD soil sample monitor has been field tested at Los Alamos and at the Fernald Environmental Management project in Ohio. Nine samples were monitored at Fernald. Detector response had flattened within 30 seconds generally for each sample. Sensitivities with such an LRAD are of order 5 pCi/g. With further analysis of the Fernald data, confidence levels can be extracted. As usual, these levels depend on the measurement time and on the amount of activity for each sample.

For an inspection, a soil sample monitor could be stowed and operated in the trunk of a vehicle, in a field office, or back at headquarters. The monitor can be made lightweight enough so that it can be moved conveniently by hand. A dozen samples could reasonably be monitored in less than a day.

Portable object monitor

It is sometimes of interest in a special inspection to check hand-tools or other small objects for traces of nuclear material. This residue of SNM can be left in grooves or cracks and on other interior surfaces even after an attempt has been made to clean the object. Air flowing around the object will collect the ions resulting from alpha particle emission even if the alpha

particles never get beyond the exterior surface of the object. An LRAD-based object monitor is appropriate for this need.

A portable object monitor is under development for the U.S. Department of Energy. The current prototype fits into a metal briefcase for transporting by hand. In laboratory tests, the prototype portable object monitor can detect total alpha activity of less than 50 dpm on an object. A clear response is obtained after tens of seconds. Although the portable object monitor is an airflow design and the hand-held surface monitor is an electrostatic design, the electronics of the former can be leveraged with the electronics of the latter - light weight and portability are the specifications.

Radon monitor

As an indicator of proliferant activity with SNM, radon is present in two conditions. The first condition is the mining of uranium ore. Large concentrations of radon occur in uranium mines, so in active mining the air within and nearby the mine will have abnormally high levels of radon. Uranium mining is not currently subject to inspection by the IAEA, so radon monitoring at foreign mines is not a viable monitoring activity. Even if mines were subject to inspection, it is likely that simple overt or covert observation of known uranium mines could provide adequate confirmation of mining activity. Nonetheless, it is useful to note that excellent radon monitors can be made available using LRAD technology.

The second condition is the processing of uranium or plutonium. Radon will be present depending on the degree of refinement of the transuranics. The radon comes directly from the radium impurities in the uranium or plutonium [6]. The long half-lives at some steps in the uranium decay chains have important ramifications. In a geologic sample of a transuranic, the sample will have had enough time (roughly the age of the earth) to come to radioactive equilibrium, in which isotopes in the chain are balanced with respect to creation and decay. However, in a pure piece of either ^{238}U or ^{235}U that was purified within the past tens of years, a negligible fraction would have since become a radon isotope. Impurities of ^{226}Ra in the ^{238}U , or ^{227}Ac or ^{231}Pa in the ^{235}U , must be present in order to result in radon.

The radon is the link in the transuranic decay chains which can migrate to a detector. Radon is a chemically inert gas while all the other species in these chains are chemically active. The other species therefore remain bound in the original strata (the ore, the metal, the molecular gases, the weapons components, or the contamination in the soil, the concrete, or on dust motes in the air). The radon, however, is liberated as a gas and is able to escape into the air within a facility.

Radon monitoring is also important when monitoring directly for airborne SNM, as naturally occurring radon provides a background which must be compensated. The noble gas penetrates any filters on detectors of airborne contamination and can then decay within the detector. Thus radon compensation is an important component of the air monitoring discussed in the next section.

An airflow LRAD monitor detects radon by drawing air through the monitor. An ion and particulate filter at the monitor inlet traps anything other than gases and very small particulates. Radon daughters in the ambient air are generally

attached to large particulates. Thus inside the radon monitor the only ion activity is due to alpha emittance from decaying radon (and due to the usual cosmic ray background.)

The response of an LRAD radon monitor must be calibrated - ideally with radon gas directly. For lab testing of radon monitors, a bottle containing uranium ore is used. The bottle is normally sealed, but a hose provides a convenient port for radon gas. For quantitative field testing, however, an environmental chamber must be used. A 24,000 L chamber exists at the Department of Energy's Grand Junction Projects Office (GJPO) in Colorado. The levels of radon set within this chamber represent the national standard for radon concentration. Two LRAD monitors were taken to GJPO for extensive testing [7]. (These monitors were actually prototype hand monitors - not optimized for radon detection - but were an airflow design.)

At the GJPO chamber, radon gas derived from 37 μCi of radium is circulated within the closed system. The radon concentration in the chamber is variable over several decades. The concentration is measured at the facility with 10 conventional radon monitors consisting of scintillators and photomultiplier tubes. (The large number of monitors is used to ensure that at least a few will still be working at the end of the test cycles since many conventional monitors last a short time before failing.) Much of the signal in many of the conventional monitors actually comes from the decay of radon progeny, so a couple of hours is necessary for their responses to equilibrate following a change in radon concentration. The response of the two LRAD monitors over time is plotted in Fig. 10. Also shown is the mean radon concentration as determined by the GJPO detector suite. The monitor responses all reflect the injection of more radon into the chamber approximately every four hours. The LRAD measurement of absolute radon concentration is seen to be excellent. The LRAD monitors responded much faster (to a change in radon concentration) than the six minutes that represents the fastest of the GJPO monitors. The response time of the LRAD monitors is essentially the five second period over which air is completely exchanged. In addition, at the lowest concentration the counting statistics of the GJPO suite are poor (according to the signal fluctuation) but do not affect the LRAD monitors' determination.

LRAD monitor response as a function of particulate levels was also observed at GJPO. The HM-1 monitor had an effective particulate filter while the HM-2 did not. Thus the HM-2 responded also to the radon progeny borne on particulates. The extra rise in HM-2 at 8 hours in Fig. 10 is due to a simultaneous increase in particulate level in the chamber. (This one increase in radon concentration is created by the introduction of ambient room air.) A quantitative analysis showed that the increased response can be accounted for.

More recently, LRAD-based prototype radon monitors were tested at GJPO. Results are currently under analysis.

Spectroscopy of the alpha particles would enable the radon isotopes and thus uranium isotopes to be determined because the radon isotopes emit alpha particles of different energies. The concentration would have to be small enough that the number of alpha disintegrations per minute be small enough that the burst of ions arriving at an electrode from each decay is separated in time between decays. Moreover, the response of the monitor would have to be flat, for which the number of

ions collected on the electrode is dependent only on the energy of the alpha particle and not on where it was created and stopped within the monitor. The LRAD radon monitor may have the flattest response of any LRAD monitor because of a cylindrical geometry and the fact that the source is a gas so that the alpha particles do not lose energy in escaping through a surface. To the extent that the response is not flat, it should be linear so that approximate corrections can be made which depend upon where in the monitor the alpha particle was stopped.

Fig. 10. Response of LRAD (hand) monitors (HM-1,2) to different levels of radon concentration in the environmental chamber at Grand Junction Projects Office, Colorado. The HM-1 had a particulate filter while the HM-2 did not. Also shown is the mean radon concentration as determined by a GJPO suite of 10 conventional detectors.

For spectroscopy the resolution of the LRAD monitor would have to be small enough to distinguish a 100 keV difference among 6-7 MeV alpha particles. This is necessary to pin down the energy of a decaying alpha particle well enough that it could be ascribed to a particular isotope of radon (or its immediate daughters) in the decay chains. Isotopes in the Thorium series also have to be considered because ^{232}Th is naturally occurring and so its daughter ^{220}Rn is generally also present as a background. Clearly, attaining this resolution with LRAD technology is a technical challenge yet to be surmounted.

Air monitor

In a reprocessing facility, some gas containing transuranics might be liberated or some trace of solids containing transuranics might be left on surfaces (with the further possibility of becoming airborne). In an enrichment facility, frequently UF_6 gas is present. In a suspected storage facility, traces of transuranics might also be present. Knowledge of process might help pinpoint how and where to check for such traces. For example, a swipe of a valve on a gas pipe can be monitored for the presence of SNM (via conventional analysis or via an LRAD swipe monitor; see below). Without such knowledge of process - or without access inside suspect areas - it would be necessary to sample the air in the area. With conventional alpha particle detection, unenclosed environments

with very localized contamination sources cannot be monitored.

An indication of the presence of SNM traces in a large room can be found by measuring the amount of ions present in the air. The room may be empty or may contain furniture, etc. Depending upon filtration, different sources of radiation could be measured with current LRAD technology. Without an ion filter, LRAD technology would be sensitive to the ions present in the room due to localized alpha decay from SNM, given that air samples containing the ions were drawn into the LRAD monitor. With an ion filter, LRAD would be sensitive only to radioactive gas, such as clouds of plutonium, uranium (UF₆), or radon (and its daughters). With a particulate filter, contamination borne on dust and reactive gases are both filtered out and only radon enters the active volume of the monitor, as discussed above.

To measure the total ionization in an enclosed area due to leaking gas, airborne contamination, or localized contamination as mentioned above, early versions of LRAD large object monitors [3] provide a prototype. These could monitor all ions and contamination in an 81 liter volume simultaneously. An unfiltered, airflow LRAD would draw in all ions, as well as airborne contamination and gases. The existing large object monitor has a throughput of at least 81 l per 5 minutes, and a sensitivity of 100 dpm total within that volume. The monitor could be left running in an enclosed room for a brief period, or could be attached to an area entrance via a door or partially open window (much as is a window air-conditioning unit.)

The chief difficulty in measuring total ionization within a large volume is in understanding anomalous readings vs. normal background. The presence of equipment such as computer terminals or phones might add to the number of ions present. Thus the typical ionization present may depend greatly on what is within the enclosed volume being sampled. The simplest treatment is to keep humans and creatures outside the volume during the measurements, and to be familiar with standard ion generators such as the equipment typically encountered.

Just as it is hard to take an initial measurement and determine whether it is anomalously high, it might be difficult to conclude from subsequent readings during a follow-up inspection that significant changes in ionization have occurred beyond normal variations in background. The ubiquitous culprit in such high readings or changes is fluctuation in terrestrial radon levels. A simultaneous radon measurement as described above can be made with an LRAD-based radon monitor in series with the total ionization monitor. Another common culprit, observed in the laboratory during LRAD development, is the presence of ions which have leaked into the volume being sampled (the room) from outside. Large fluctuations have been observed arising from weather and from cyclical traffic patterns outside. Hence, the more airtight is the volume being sampled, the smaller the variation in background to be expected.

Loose contamination which has become airborne, or radioactive gases, could be detected using an LRAD air monitor with electrostatic filtering. The filter would remove the gross ionization in the ambient air. To the extent that the filter is a poor particulate filter, airborne contamination could enter the chamber of the monitor. Again, this configuration should be coupled to an LRAD radon monitor, in order to

distinguish radon from other gases and from loose contamination.

Lab testing of an airborne contamination monitor has not yet been executed because the environmental health and safety concerns regarding free loose contamination. One issue in field use will certainly be the unknown level of a normal background in an initial inspection. However, the background will be less of a problem for an airborne contamination monitor than for a gross ionization monitor.

Swipe monitor

When speed of inspection is important, or when there is knowledge of process, it may be desirable to take a standard swipe of an object or surface, and then (perhaps later or elsewhere) monitor the swipe. For example, a pipeline valve might be identifiable in a facility as a possible or previous carrier of a uranium gas or liquid solution. Swiping around the valve could concentrate any contamination onto the swipe.

A swipe monitor has been proposed based on a very small, electrostatic LRAD monitor. The swipe is placed in a drawer at the bottom of the monitor. Proof-of-principle tests have been encouraging as to the sensitivity of such a monitor relative to a traditional swipe counting monitor. Issues relate more to the process of swiping than to the use of the swipe in an LRAD monitor.

Liquid monitor

During an inspection of a facility, it is conceivable that some liquid might be suspected of contamination with SNM. For example, wash water used on equipment or perhaps on walls and surfaces for the purposes of clean-up might remain. Standing liquids in tubs or pipes might be present during the inspection. Unknown or otherwise suspect solutions might be stocked. Ordinary piping in a reprocessing facility will be expected to carry much contaminated water. The obvious target of an inspection would be a reprocessing facility which has been declared shut down. The liquid in a reactor facility, on the other hand, should be uncontaminated. Indications of contamination are more a matter of safety than of non-proliferation. Outside of any facility, rainwater "washing" off the roof and walls could concentrate any contamination present on those surfaces. Such standing water outside would be a good candidate for testing.

It is possible to test quickly small amounts of liquid for the presence of SNM contamination with LRAD technology. For the scenarios described above, a sample of the liquid is poured into a stainless steel tray and placed in a small, enclosed LRAD monitor. Essentially, the detector is as described for soil sample monitoring. The liquid sample substitutes for the soil sample shown in Fig. 9. The LRAD liquid monitor will be sensitive to alpha emitters floating on the liquid or suspended very near the surface. The response of the detector will also depend on the surface area: response will increase as more liquid is added to cover the bottom of the tray, but will remain constant as liquid is added to top off the tray. The LRAD monitor would serve as a screening tool. The chemistry of the liquid is unimportant unless there is a large amount of beta emitters in solution or the liquid is highly

corrosive to the stainless steel tray. Also, extreme differences in density of the liquid could affect the detector response - increasing density would mean that less depth below the liquid surface would be monitored.

A prototype LRAD liquid monitor has been tested at a Los Alamos National Laboratory waste processing facility [8]. The radioactive liquid used in the test had an alpha activity of 280 pCi/liter as determined by independent analysis to a level of ± 40 pCi/liter. (This level of contamination represented 1/150 the typical level of activity for liquids at that facility.) The LRAD detector noted a level 3.5 times the background level, with 1% sensitivity. In repeated sampling, the average signal was 4 times the background level, with a deviation of 4%. No activity above background was left on the tray after the measurements. Given these results, the sensitivity of an LRAD liquid monitor in that environment could be conjectured to reach 70 pCi/liter. With a response on the order of minutes, LRAD technology provides a fast, sensitive package for testing liquid samples for SNM contamination during facility inspections.

Personnel monitor

In a challenge inspection it might be desirable to monitor personnel for SNM contamination. Such a monitoring step could augment the monitoring of tools and equipment with the object monitor described above. While it is unlikely that cooperative inspection agencies would monitor foreign personnel, it is conceivable that inspectors could be monitored after traveling through suspect rooms or areas. As a means of passively gathering contamination onto the personnel, this would depend largely on how loose (rather than fixed) the contamination is.

Two prototype LRAD monitors have been constructed for monitoring personnel in plutonium processing facilities. These portable monitors can also be used for monitoring personnel in an inspection. Each LRAD monitor is an airflow design - one just large enough to monitor a hand, the other in the form of a pipe which can monitor an arm. The airflow implementation is ideal for picking up contamination on any surface of a hand or arm. Traditional monitors are unlikely to get register alphas emanating from contamination under the fingernails or between the fingers, for example. Such "out of the way" places are likely locations for contamination to collect and not get properly washed away. The "doors" in both of these detectors consist of large rubber irises that can be closed onto the wrist or arm to create an air seal. The irises are made of conductive rubber in order to establish a Faraday cage.

The response of the hand monitor to plutonium sources has been studied in the lab as a means of calibrating the monitor response. The sources used were disks on which ^{239}Pu was deposited. A 100 dpm source is clearly discernible above the background current level.

No field tests of either the hand or arm monitor have been carried out, although the hand monitor was installed at the plutonium processing facility at Los Alamos National Laboratory for several weeks.

The laboratory tests have been sufficient to demonstrate that some issues remain regarding the hand and arm monitoring. The necessity of creating a Faraday cage during monitoring was mentioned above. This prevents capacitive

coupling of the outside world (i.e. beyond the monitor) to the electric fields within the monitor. Unfortunately, the diameter of a wrist or an arm is large enough to permit such coupling. This problem is solved if the appendage wears conductive material. In practice, such a requirement is difficult to achieve during an inspection - unless the personnel just happen to wear gloves of conductive material.

A similar problem in monitoring appendages is the static charges on an appendage when first introduced into the monitor. Without a conductive surface (glove) to conduct away such charge quickly to the monitor box, it can take 10 minutes for the static charges to drain away through the air. Again, the best solution is for gloves of conductive material to be worn - beneath potential contamination as well as before insertion into the monitor.

It is also possible to monitor a whole person in a very large airflow LRAD monitor [9]. Such a monitor would essentially be a telephone-booth sized object monitor. A fan manifold serving as the top of the chamber would draw air through the chamber, over the individual and the clothes and objects on his person. The ion collection grid would be placed just underneath the fan manifold, to catch the ions drawn from alpha emission from all surfaces in the enclosure. The air intake would be provided by a HEPA or electrostatic filter in the floor of the booth.

The whole body monitor is unlikely to be used in inspections at remote facilities because the size of the monitor does not lend itself to portability. However, one can conceive of the air intake filter/flooring being carried as a unit, separate from a unit consisting of the fan manifold. Telescopic struts could create the frame of the enclosure. The enclosure walls could consist of an airtight, lightweight material wrapped around the frame.

An LRAD object monitor large enough to contain a person will have a large background due to cosmic ray activity in the chamber and the possible presence of radon in the surrounding environment (each contribution proportional to the volume of the chamber). A monitor of this size has not been prototyped; however, large object monitors have been constructed. The active volume of such a monitor is $81,000 \text{ cm}^3$. The response of this monitor to ^{239}Pu alpha-particle sources is quite linear, with a conversion of 9.6 fA per 100 dpm. The background signal is rather large for an LRAD monitor, as expected for the larger volume.

It is possible to reduce this background via any of four techniques. Passive shielding would reduce the contribution to the response of external radiation sources such as cosmic rays. This method would add to the weight of the portable booth and is untenable. A second, reference LRAD-based monitor could be used to provide a simultaneous background measurement. Assuming the two monitors were matched, the reference signal could be subtracted - thus removing the contributions from backgrounds. The size could range between the booth size and a much smaller LRAD monitor. This solution is also unwieldy for a portable monitor. A partial compensation can be made by attaching a small LRAD monitor onto the booth, the former drawing air from the latter. Such a monitor would sample the radon level in the booth directly, but again, its response to both radon and to cosmic rays would have to be scaled to match the response of the booth. Lastly, background measurements made in the booth immediately before the

personnel steps in for an actual measurement could be subtracted from the actual measurement. This method is not ideal because two large numbers might get subtracted in order to find a potentially small number representing the contamination of the person. However, the last method is the simplest.

A separate issue with the whole-body monitor is the background created only when personnel are in the monitor - ion sources present with the person but not related to alpha particles. One such source is the possible presence of static electricity on clothing. The clothing of a person in the booth may have static charges which could take time to drain away. Conversely, the clothes could trap the charges liberated in legitimate alpha particle events until an equilibrium was reached - especially if the person had been discharged via humid air or surface contact just prior to entering the booth. The time required to reach the point of no charge/discharge could vary with the amount and type of cloth. A different potential source of ions is the mere breath of the person. This issue would have to be explored early in the development of a whole-body, LRAD-based monitor in order to characterize the degree of the problem and the viability of the application.

Barrel monitoring

Barrels present at a facility under inspection might contain nuclear material or process waste. The barrels might also contain shielding in an effort to conceal gamma-ray activity. If the barrels are cracked or other damaged, the damaged areas of the barrel are prime locations to check for leaks of SNM. Swipes can be taken, and monitored with an LRAD swipe monitor. A hand-held surface monitor could be placed on the surface of the barrel. The barrel could be placed in a generic LRAD-based object monitor. These LRAD-based monitors have been discussed above. Alternatively, a barrel monitor optimized for such a purpose could be constructed. The monitor would be similar to an object monitor except without the airflow implementation. The barrel could form one of the electrodes in an electrostatic design, for increased efficiency over airflow designs.

STORAGE AND PORTAL MONITORING

One aspect of nonproliferation is the control and accountancy of nuclear material. This control is effected for material in storage, and for objects and personnel entering and leaving the area. Scenarios are identified below for which monitors based on LRAD technology could aid in such control and accountancy.

Nuclear munitions monitor

The issue of verifying that a transportation or storage container actually holds SNM without measuring sensitive parameters (shape, mass, etc.) loom large in material control and accountancy. A potentially insensitive parameter has been identified which respects the transparency issues but might be a reliable signature of the presence of SNM. The confidence of

this determination can be increased by simultaneous measurement of some other parameter, such as gamma-ray activity or temperature.

The parameter in question is the total ionization created in surrounding air from the SNM container. The process by which such ionization is created is for which gamma rays emitted by the SNM scatter in the material (typically metallic) comprising the container, creating electrons. These electrons are the ionizing particles analogous to the alpha particles in the normal LRAD application.

Now an LRAD-based monitor is roughly 1000 times less sensitive to electron particles (betas) than to alpha particles because an electron deposits far less energy in a unit distance than an alpha particle. Therefore a much larger volume of air would be needed to completely trap the electrons. However, a great many electrons can be liberated by the gamma rays.

As a proof-of-principle test of this process and of the sensitivity of an LRAD-based monitor, a large quantity of ^{239}Pu was placed within an LRAD object monitor. An aluminum heat sink served as a mock container. This assembly registered a signal 50 times greater than the background - which itself was already high due to the environment. The heat sink alone was not the cause the signal. When placed in the LRAD object monitor alone, the heat sink gave no signal above background. Moreover, a swipe of the outside of the heat sink yielded no surface contamination. Therefore the heat sink itself was essentially not activated and not contaminated.

Beyond the proof-of-principle test, more experimentation is necessary regarding the specificity of this signature of SNM before such LRAD-based munitions detectors can be developed and deployed.

Personnel monitoring

Generally, personnel are often monitored for gamma ray and neutron emitters at a portal monitor upon entering or exiting a facility. Sometimes hand-held probes are used to search for alpha emitter contamination as well. A sensitive alpha particle monitor could be useful in conjunction with gamma-ray portal monitoring. LRAD-based personnel monitors have been discussed above.

UNATTENDED MONITORING

Occasional examination of a facility or site by an inspector is frequently insufficient to establish high confidence that no proliferation activities are occurring. Continuous, unattended monitoring for signatures of proliferant activity is usually desirable. Unattended monitoring requires the capability for either storage of data or temporary storage of data to remote data collection points.

One platform for unattended monitoring is the Modular Integrated Monitoring Systems (MIMS) program [10]. The MIMS program seeks to combine different sensors of proliferant signatures, and to marry the sensor suite to a standard architecture for data communication and for user interface.

The use of alpha particle emission as a signature of proliferant activity has often been limited by the low sensitivity of unattended, real-time alpha particle detectors. Alpha particle detection utilizing LRAD technology can serve as a sensor. Moreover, the technology can be integrated with other sensors on the platform of MIMS in order to increase confidence in indicators of proliferation activities.

Several model scenarios are envisioned which can be addressed with sensors based on LRAD technology. These scenarios include process monitoring (facility effluent and external facility monitoring), facility monitoring (portal monitoring), and item monitoring (storage facility corraling). LRAD-based sensors fulfill most of the issues identified for the MIMS program: environmental health and safety, exportability, reliability, maintainability, power consumption, miniaturization, ruggedness, and cost effectiveness. Particular applications are discussed below.

Airborne contamination

Gaseous effluents from a facility can be monitored with an air monitor such as has been described previously. The LRAD air monitor could sample the air for transuranic contamination. Gross ionization could be monitored at very high through-put. This is unlikely to be specific enough to identify alpha decay as a contribution to ion concentration for various facilities. Instead, the air stream could be filtered electrostatically to remove ambient ions. Then, as discussed previously, the transuranics could decay within the volume of the air monitor, producing ions and therefore a signal. Depending upon the air flow, the monitor could either encompass the entire cross section of the emission stack, or could sample a portion of the air flow.

Lab testing of such a monitor with contaminated air has not been done yet because of environmental safety and health issues. Potential issues in field use include the uncertainty in the background ion activity to be encountered. It must be noted that pending further development of spectroscopic capabilities of LRAD technology, isotopics can not be determined and so the confidence level on the source of a large LRAD air monitor signal is reduced somewhat. For example, enrichment of leaking UF₆ gas could not be determined at this time.

On the other hand, the ruggedness and reliability of an LRAD air monitor are advantages. The monitor will work regardless of what gases are present in the effluent - unless the gases are highly corrosive. For alpha emitter contamination, the air monitor can naturally be combined with the LRAD radon monitor discussed above. This coupling would permit subtraction of the ubiquitous contribution to alpha emission from radon decay.

Liquid-borne contamination

Similar to the monitoring of gaseous effluents, liquid effluents can be monitored with an LRAD sensor. The detection of alpha emitters in liquids using an LRAD liquid sample monitor was discussed above. As with gaseous effluents, some portability in the monitor can be traded off for size and ruggedness. Aqueous contamination monitoring would involve different liquid handling than just a tray. The obvious scenario is installing a monitor within a pipeline. The liquid

would flow continuously through a deep version of the tray, with the ion collection apparatus situated above the liquid.

The continuous flow of liquid raises the issue of splashing as well as condensation, although these issues are tenable. Another issue is the mixing of incoming liquid so that a uniform distribution of contamination within the liquid in the monitoring chamber is maintained. Otherwise, the same considerations apply as for the liquid sample monitoring. Again, the chemistry is unimportant unless a high concentration of beta emitters is present. The densities of liquids anticipated to flow through the monitor should be known - or at least, the lack of extreme densities.

The testing of the liquid sample monitor serves as a proof-of-principle. We note the 70 pCi/liter sensitivity that can be anticipated.

Large gamma-ray activity

In order to note the movement of nuclear material into or out of a facility, a gamma-ray monitor could be placed nearby. Normally, this would be considered portal monitoring, and traditional, efficient scintillating detectors would be used. If cost and reliability are a factor, however, traditional portal monitoring has a high unit cost and is usually maintained periodically by personnel.

A gamma-ray detector based on LRAD technology could be very useful in long-term, unattended monitoring. Such a detector works by collecting the ions produced in photon interactions in the walls of the detector. The key advantage of the LRAD-based gamma detector over the conventional gamma-ray detector is ruggedness and durability. Since the LRAD detector is not composed of a photomultiplier tube or a sensitive and expensive crystal, it can be cost effectively mass produced and left in unforgiving terrain. Also, with the low power demands of the detector it can be left unattended for multiple years. An easily achievable scenario would involve placing and concealing the LRAD gamma-ray monitor in an area where there should not be any movement of nuclear material. The monitor would take data continuously and send it to a receiver where the baseline could be monitored. Any large increase in signal would easily be detected and would help to provide proof that nuclear material was being moved.

An LRAD-based gamma detector would be a large cylindrical electrostatic detector with the walls of the cylinder acting as one electrode and a rod along the axis of the cylinder acting as the other electrode. The advantage of this configuration would be to maximize the volume of the detector while minimizing the distance the freed ions would need to drift before the ions were collected. The thickness of the metal walls would be maximized for a number of reasons. First, the thicker walls would lead to a more durable detector. Secondly, the thickness of the walls would correspond to the maximum range of the electrons generated in the walls. By having the walls thicker but not larger than the maximum range of the electrons you maximize the number of electrons generated and collected in the detector.

A proof-of-principle test was conducted at Los Alamos National Lab over a 2 month period ending in May, 1994. The test involved placing an LRAD large object monitor at known distances ranging from 300 m to 1.6 km, and running a critical assembly to different power levels as a source of

gamma rays. Also included in the test was a comparison between the new gamma detector (based on LRAD technology) and the established detection capabilities of a Sodium Iodide (NaI) detector.

It must be noted that the detector used in the gamma tests, is not the most efficient detector that could be designed using LRAD technology. In fact the large object (airflow rather than electrostatic) monitor utilized for the test is usually used to minimize contaminated waste streams [11].

Locations for the detectors were chosen for their distance from the critical assembly as well as whether there was a direct line of sight from the critical to the detector or whether the line of sight was blocked by earth (rock, trees, etc.) Having the detector at a non-line of sight location meant that the signal was mainly due to skyshine, the redirection of radiation by scattering events in the atmosphere. The data from both the NaI and the LRAD monitor (current in femptoamperes) were normalized to a current (10^{-5} RAP A) in an ionization chamber located next to the critical assembly that is used to measure the criticals power level and thus the total output fluence. The detector response is plotted as a function of distance in Fig. 11.

Fig. 11. Response of a mock LRAD gamma-ray monitor and a NaI detector at different distances from a gamma-ray source (a critical assembly).

The characteristics of the curves for both the LRAD and the NaI detectors are similar in nature for the skyshine locations, with only a slight difference at distances less than 500 meters. Insufficient data has been taken for the line of sight locations for a conclusion to be drawn, partly due to the lack of locations at large (>600 m) distances due to the geographical nature of the area.

Storage vaults

Monitoring the air in sealed vaults would indicate any breach of the seal. Given that the ion concentration in the air within a sealed vault is fairly stable, an ion monitor will immediately register such a breach because of the 10^5 - 10^7 ions/cm³ that would rush in with the outside air. An LRAD air monitor without input filtering is capable of this, as it can

easily see a point source of 100 dpm - or 1.4×10^6 ions within a volume of 6000 cm³. The LRAD air monitor would be coupled to a radon monitor, as the major component of a background signal would be the varying level of radon present.

REMOTE MONITORING

It might be useful to search for gamma-ray activity from afar. Such an endeavor could be considered a remote "screening" of facilities to check for gamma-ray production. The test of LRAD-based monitors as gamma-ray detectors described above show that such an air-ionization gamma-ray detector holds promise for use at large distances from the gamma-ray source. A scenario would involve the overflight by helicopter at low level, or the drive-by in a van. The small unit cost and ruggedness of an LRAD-based gamma-ray monitor suggest their possible use in such scenarios.

TRANSPORTATION

Scenarios exist in which facilities have not been identified by inspection authorities yet the possibility of movement of nuclear material exists. With no particular facilities to inspect, it may be feasible to establish checkpoints on transportation routes. Potential monitors are mentioned below.

Truck monitor

Trucks with cargo bays might be inspected at checkpoints for the presence of (or traces of) nuclear material. An LRAD air monitor might be used to check the gross ionization or the potentially contaminated dust in the large cargo volume. The truck may be empty, or full of cargo. Interestingly, the cargo might include produce from fall-out regions. The considerations discussed above for air monitors apply. Careful comparison to other radiation detection measurements would be necessary before development of such a monitor is undertaken.

Vehicle filter monitor

The air and water filters in vehicles might catch and concentrate airborne contamination as the vehicles drive around a region. These filters could be inserted into small LRAD detectors at checkpoints for subsequent monitoring of alpha contamination.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of K. S. Allander, R. D. Bolton, J. A. Bounds, S. E. Garner, J. D. Johnson, and M. Rawool-Sullivan. We are grateful for discussions with K. E. Apt, D. A. Close, M. W. Johnson, R. E. Kelley, M. F. Mullen, and J. R. Phillips.

REFERENCES

- [1] D.W. MacArthur, K.S. Allander, J.A. Bounds, and K.B. Butterfield, "Small Long-Range Alpha Detector (LRAD) with Computer Readout", Los Alamos National Laboratory internal report LA-12199-MS, October 1991.
- [2] D. W. MacArthur, "Long-Range Alpha Detector (LRAD) Advanced Concepts," Los Alamos National Laboratory internal report LA-12225-MS, December 1991.
- [3] R. W. Caress, D. W. MacArthur, K. S. Allander, J. A. Bounds, M. M. Catlett, S. E. Garner, J. D. Johnson, J.P. Johnson, D. A. Rutherford, "LRAD-Based Airflow Monitors", Los Alamos National Laboratory internal report LA-12742-MS, March 1994.
- [4] D. W. MacArthur, K. S. Allander, J. A. Bounds, R. W. Caress, M. M. Catlett, D. A. Rutherford, "LRAD Surface Monitors", Los Alamos National Laboratory internal report LA-12524-MS, February 1993.
- [5] J. A. Bounds, "LRAD Alpha Monitoring for Sandia National Laboratories", Los Alamos National Laboratory internal report LA-UR-94-751, April 1994.
- [6] D. E. Martz, *Radon Behavior and Radon Assessment: A Training Course for Professionals*. Colorado: UNC Geotech Radon Laboratory, U.S. Department of Energy Grand Junction Projects Office.
- [7] J. P. Johnson, R. D. Bolton, S. E. Garner, K. L. Benham, G. L. Langner, Jr., "LRAD Radon Test Results", Los Alamos National Laboratory internal report LA-UR-94-186, February 1994.
- [8] J. D. Johnson, "Report on LRAD Phase I Bench Tests at TA-50", Los Alamos National Laboratory Internal Memorandum NIS6-94:0323JDJ, March 21, 1994.
- [9] Duncan W. MacArthur, Krag S. Allander, John A. Bounds, J. Lee McAtee, *LRAD-Based Alpha-Particle Contamination Monitoring of Personnel and Equipment*, Nuclear Technology, Vol. 102, p. 270, May 1993.
- [10] Department of Energy National Laboratories, *The MIMS Program for Arms Control and Nonproliferation*. U.S. Department of Energy Program Plan, February, 1994.
- [11] D. W. MacArthur, K. S. Allander, J. A. Bounds, M.M. Catlett, R. W. Caress, D. A. Rutherford, "Alpha Contamination Monitoring of Surfaces, Objects, and Enclosed Areas," *IEEE Transactions on Nuclear Science*, vol. 40, pp. 840-845, August 1993.

**DATE
FILMED**

11 / 1 / 94

END