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MEASUREMENT OF SURFACE ALPHA CONTAMINATION USING ELECTRET ION CHAMBERS

Principal Investigator:

M.A. Ebadian, Ph.D.

Florida International University

Collaborator:

S.K. Dua

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HEMISPHERIC CENTER FOR ENVIRONMENTAL TECHNOLOGY (HCET)

Florida International University, Center for Engineering & Applied Sciences

10555 West Flagler Street, EAS-2100, Miami, Florida 33174

305-348-4238 • FAX: (305) 348-1852 • World Wide Web Site: <http://www.hcet.fiu.edu>

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Principal Investigator

M. A. Ebadian, Ph.D.
Hemispheric Center for Environmental Technology
Florida International University
Miami, FL 33174

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**Florida International University
Collaborator**

S. K. Dua
Hemispheric Center for Environmental Technology
Florida International University
Miami, FL 33174

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EXECUTIVE SUMMARY

Electret ion chambers (EICs) are known to be inexpensive, reliable, passive, integrating devices used for measurement of ionizing radiation. Their application for measurement of alpha contamination on surfaces was recently realized. This two-year project deals with the evaluation of electret ion chambers with different types of electrets and chambers for measurement of surface alpha contamination, their demonstration at U.S. Department of Energy (DOE) sites, a cost-benefit comparison with the existing methods, and the potential deployment at DOE sites.

During the first year (FY98) of the project, evaluation of the EICs was completed. It was observed that EICs could be used for measurement of free release level of alpha contamination for transuranics (100 dpm/100 cm² fixed). DOE sites, where demonstration of EIC technology for surface alpha contamination measurements could be performed, were also identified.

During FY99, demonstration and deployment of EICs at DOE sites are planned. A cost-benefit analysis of the EIC for surface alpha contamination measurement will also be performed.

1.0 INTRODUCTION

1.1 BACKGROUND OF THE PROBLEM

In and around nuclear plants such as spent fuel vitrification plants, fuel reprocessing plants, uranium plants, thorium plants, waste storage facilities, reactors, and radiological laboratories, surfaces (floors, walls and ceiling, and equipment) and soil may get contaminated with alpha-emitting radionuclides such as uranium, thorium, radium, americium, or plutonium. It is important to measure and classify such contamination as being above or below the permissible levels. The permissible levels of total and removable alpha contamination for transuranics are 100 and 20 dpm per 100 cm², respectively. The U.S. Department of Energy (DOE) has a requirement for low-cost and reliable methods for measuring low levels of alpha contamination. At present, surface alpha contamination is measured by hand-held alpha detectors or by wipe test. In a wipe test, a known area of the surface is wiped with a filter paper, which is subsequently counted in a counter. This test gives information about the transferable contamination only. Hand-held alpha survey meters are difficult to use on floors, particularly when large areas are to be surveyed and when contamination level is low. Floor contamination is measured by floor monitors. Floor alpha contamination monitors suffer from low sensitivity. Further, since alpha particles have a small range (~4 cm in air or ~5 mg cm⁻²), the detector window should be extremely thin and the detector should be placed very close to the floor. This often leads to the damage/puncture/contamination of the detector/window.

Electret ion chambers (EICs) are an alternate technology for measurement of surface alpha contamination. These are cheaper than most of the devices used for alpha contamination measurement, particularly low contamination levels. A single charge reader (Rad Elec, Inc.)¹ costing nearly \$ 2000 is required, and a large number of electrets (\$12.50 each) loaded in chambers (145 ml: \$15 or 960 ml: \$70) can be simultaneously deployed to measure surface contamination in any large facility and picked up after the exposure. Survey meters (\$1000 to \$2000 each), on the other hand, need to be held or mounted in a position for 10 to 20 minutes for statistically significant counts. This requires the surveyor's continuous presence in the area, resulting in high personnel exposures or use of large numbers of expensive survey meters. Electrets can be used again and again so long as their voltage is above a certain value. EICs are usable in adverse conditions of high humidity and temperatures (MARSSIM 1997). EICs can also be used for measurement of radon, alpha, beta, gamma, and neutron radiations (Kotrappa et al. 1981; Kotrappa et al. 1982; Campos et al. 1982; Kotrappa et al. 1983; Dorschel and Pretzsch 1984; Kotrappa et al. 1992a, 1992b; Dua et al. 1995; Meyer et al. 1994; Meyer et al. 1995).

An EIC is a passive charge-integrating device. Its integrating property enables it to collect ions produced by alpha radiation over a long time and hence detect very low levels of alpha contamination. The EIC can be used without a window or with a thin (0.8 mg cm⁻²) aluminized Mylar² window. The aluminized Mylar prevents contamination of the chambers. It also eliminates the interference of static charges on dielectric materials on ion collection. It is

¹ Rad Elec, Inc., 5714-C Industry Lane, Frederick, MD 21701.

² Mylar is a registered trademark of duPont de Nemours and Co., Wilmington, DE 19898.

important to note that the use of an aluminized Mylar window degrades the energy of alpha particles; thus, the alpha particles have less energy to expend in the chamber air. This results in lower sensitivity of the EIC with a window than without. A puncture of the window due to a rough surface does not affect its performance since the chamber contains air at ambient temperature and pressure. Electret chambers are low cost enough to be disposed of when contaminated. EICs are light-weight (maximum mass 150 g) and can be placed flush against any surface (floor, wall, or ceiling) using an adhesive tape.

1.2 PURPOSE OF THIS INVESTIGATION

An EIC is composed of an electret (an electrical analog of a magnet) loaded inside a chamber. Electrets are commercially available in three thicknesses, which have different sensitivities. EICs are available with chambers in two volumes, 145 ml and 960 ml. The EIC can be used without a window or with a thin (0.8 mg cm^{-2}) Mylar window. The different combinations of electrets and chambers and Mylar window affect the sensitivity, and hence the level of contamination that the EIC system can measure.

Meyer et al. (1994) have characterized the 145-ml chamber for surface alpha contamination. The purpose of this investigation is to cover some additional factors that have bearing on the response of the 145-ml chamber, extend the study to the 960-ml chamber, and recommend suitable chamber-electret combinations for measurement of different levels of surface alpha contamination.

2.0 FACTORS THAT INFLUENCE EIC RESPONSE

An electret ion chamber (EIC) consists of an electret loaded into an ionization chamber. For measurement of alpha contamination, the EIC is first exposed to reference calibration sources, and the response of the EIC (change in electret voltage per disintegration) is determined. There are a number of factors that influence the response of the EIC. Calibration of the EIC system should be performed for each of these factors addressed below:

- **Electret Voltage:** A manufacturer of electrets (Rad Elec, Inc.) supplies electrets with an initial voltage of approximately 750 V. As the electrets are discharged by ionization in the chamber, their voltage reduces. The drop in voltage depends, besides the radiation intensity and exposure time, on the electret voltage. Since the electret voltage, within its useful range, can have any value, it is important to determine an expression that relates the response with the electret voltage. Then using this relationship, contamination for any voltage change can be determined.
- **Alpha Energy:** For a given surface activity, the number of ion pairs produced in the chamber air volume depends on the alpha particle energy. High-energy alpha particles produce more ion pairs than low-energy alphas, if they expend their entire energy in the chamber air volume. Since EICs don't possess spectrometric capability to distinguish between alpha emitters, it is necessary to determine the range of responses expected for the different alpha-emitting materials likely to be encountered.
- **Location of Contamination:** The response of the EIC to a point source depends on the position in relation to the chamber base at which the source is located. For a given electret voltage, the electric field is different at different locations, and so the response is different.
- **Chamber Dimensions:** Commercially available ion chambers for alpha contamination measurement are of 145 ml and 960 ml volumes with open window areas of 48.5 cm² and 180 cm², respectively. The shape and dimensions of the two chambers are different and so are the electric field gradients for a given electret voltage. The strength of the electric field gradient affects ion collection and hence the response of the EIC.
- **Electret Thickness:** Electrets are available in three different thicknesses, 0.127 mm, 1.524 mm, and 4.572 mm. The sensitivity of the electret depends on the electret thickness.
- **Mylar Window:** For measuring alpha contamination on surfaces, it is a good practice to cover the open window of the EICs with thin (<1 mg) aluminized Mylar. The aluminized Mylar prevents contamination of the chambers. It also eliminates the interference of static charges on dielectric materials on ion collection. Use of an aluminized Mylar window degrades the energy of alpha particles; thus, the alpha particles have less energy to expend in the chamber air. A thick window (> 7 mg cm⁻²) will stop most of the energetic alphas emitted from radioactive materials.
- **Contamination Levels:** Usually, EICs are calibrated by using alpha sources of low radioactivity, but at times high contamination levels may be encountered. Since at high contamination levels the ion pair density is high, the loss of ions due to recombination is also expected to be higher than at low contamination levels.

- **Effect of Gamma and Radon Backgrounds:** EICs respond to any radiation that produces ion pairs in the chamber volume. It is, therefore, important to determine the interference from background radiations.
- **Chamber-Electret Combination:** There is a need for a suitable combination of chambers and electret thicknesses that can provide measurement of different contamination levels at desired exposure times.

3.0 PROJECT DESCRIPTION

This two-year project began on November 1, 1997. Given below are the tasks and the status for the first year (FY98):

Task 1: Search for a DOE site for demonstration and deployment.

The sites identified for demonstration and deployment are Savannah River, Oak Ridge, and Rocky Flats

Task 2: Calibration of EICs.

Calibration of the EICs in terms of change in electret voltage per disintegration was completed.

Sub-task 2.1: Response of EIC for different electret voltages

The response of the EIC at different voltages on electret was completed.

Sub-task 2.2: Response of EIC for different alpha calibration sources

The response of EICs for different alpha calibration sources, such as ^{237}Np , ^{239}Pu , ^{241}Am , and ^{244}Cm with alpha energies ranging from 4.7 MeV to 5.8 MeV, was determined. Influence of different contamination levels on the response was also determined. The work is complete.

Sub-task 2.3: Response of EIC for different positions of the alpha calibration source

The response of the EIC for a given source was determined for any position of the source at the chamber base. The response was also determined for a source of the same area as the chamber opening. The work is complete.

Sub-task 2.4: Response of EIC for electrets of different thicknesses

The response of the EIC was determined for commercially available electrets of three thicknesses (0.127 mm, 1.524 mm and 4.572 mm). The work is complete.

Sub-task 2.5: Response of EIC with an aluminized Mylar covering

At times a thin layer of aluminized Mylar is interposed between the contaminated surface and the open faced (windowless) EIC to measure the contamination. This Mylar prevents contamination of the EIC. It also prevents dielectric surfaces from interfering in ion collection by electret. With the incorporation of Mylar between the EIC and alpha source, alphas dissipate some alpha energy in the Mylar resulting in decreased ion pairs in the chamber volume. The attenuation in the response of the electret due to incorporation of the Mylar was determined.

Task 3: Useful range of EIC

Different combinations of the electret thicknesses and chambers produce different responses (change in electret voltage per disintegration). Since electrets can be used within a limited surface voltage range (~ 200 to ~750 V), the total contamination that can be measured depends on the EIC combination used. The useful range of the EIC was determined. The work is complete.

Task 4: Influence of environmental radon and gamma radiation

EICs respond to any radiation as long as it can produce ion pairs in the chamber air volume. The electret voltage change, which a given level of radon or gamma radiation produces, was determined, and it must be subtracted from the total voltage change to account for alpha contamination.

Task 5: Optimization of response

Response of the EIC system was checked for various parameters described in tasks 2 to 4, and a suitable set of parameters were recommended.

Task 6: Demonstration at a DOE site

A demonstration will be performed at a DOE site. Based on the suggestions from the site personnel changes in the system or study of additional parameters will be performed and the system will be made field-worthy. Demonstrations performed by other investigators at Rocky Flats and Oak Ridge have concluded that the technology is capable of measuring surface alpha contamination below free release levels.

Following are the tasks planned for FY99:

Task 1: Cost-benefit analysis

Based on the demonstration performed at a DOE site in FY98, FIU will perform cost-benefit analysis of EIC technology for a surface alpha contamination measurement system, comprised of different types of commercially available chambers and electrets. A comparison of equipment cost, cost per measurement, and safety issues will also be made with the baseline technology. This analysis will be performed by FIU-HCET.

Task 2: Deployment plan

During the FY98, some of the sites identified for the deployment of technology for measurement of surface alpha contamination, were Rocky Flats, Fernald, Savannah River, and Hanford. Currently, the Savannah River Site is inviting technology vendors for expression of interest in a 321-M large-scale demonstration and deployment project. The electret ion chamber system is intended to be used for characterization of "Overheads" before and after cleaning. FIU-HCET is collaborating with Rad Elec, Inc., the manufacturers of EICs for this project. We are also discussing the possibility of deployment of the EIC system at Hanford with members of the Canyon Disposition Initiative Technology Working Group.

Based on the calibration and demonstration of the system at one or more of these sites and suggestions from the site personnel, plan for deployment of the system will be finalized.

Task 3: Deployment at a DOE site

Protocol for measurement of contamination, handling procedure for electrets, calibration factors, equations and relevant information on the system will be prepared and made available to the site personnel. The protocol will also describe procedure for accounting for surface beta contamination and gamma radiation and radon. The CMST-CP focus area and D&D focus area management will be involved in all stages of the projects from demonstration to deployment. The system, after successful demonstration, will be deployed at one or more sites.

Task 4: Follow-up

A liaison between site personnel and the commercial technology vendor will be maintained to ensure smooth flow of information, equipment and components and technological developments in the EIC /charge reader/related systems.

4.0 MATERIALS AND METHODS

An EIC consists of an electret (a charged Teflon³ disk) loaded inside an ion chamber. Ion chambers are commercially available in two volumes, 145 ml (open area 48.5 cm²) and 960 ml (open area 180 cm²). Electrets are available in three thicknesses. Table 1 gives the details of the EIC. The electret serves as a source of electrostatic field and collects ions produced by alpha radiation in the chamber air. It also serves as a sensor of radiation. Due to collection of ions, its surface charge (voltage) gets reduced. The voltage is measured using a portable volt reader. Figure 1 shows a photograph of an electret, electret chambers and the charge reader. The rate of reduction of the voltage gives a measure of alpha radiation. The calibration is achieved by locating standard sources, emitting alpha particles of different energies, at the bottom of the chamber and determining the response factors (change of voltage per unit disintegration). Table 2 presents the details of different alpha-emitting calibration sources.

Calibration has been performed for 145-ml and 960-ml chambers, with and without a Mylar window. For calibration, an electret of a particular thickness, an ion chamber (145 ml or 960 ml), and an alpha source are selected. The voltage on the electret is read (initial voltage). The electret is placed in a chamber and exposed to the alpha source for a known time. After the exposure, the electret is unloaded from the chamber, and its voltage is read again (final voltage). Table 3 shows data for a 145-ml windowless chamber with a short-term (ST) electret and an ²⁴¹Am source with its center aligned with the chamber centerline. The first row of this table shows the initial voltage, the final voltage, change in voltage (difference between the initial and the final voltage), the exposure time in seconds, the strength of the alpha source in Bq, the disintegrations, mid-point voltage (mean of the initial and the final voltage), and response of the EIC (change in voltage per disintegration). The total disintegrations to which the electret is exposed are obtained by multiplying the source disintegration rate with the exposure time (disintegrations = Bq (disintegrations per second) x exposure time in seconds). These measurements are repeated and are shown in subsequent rows. The initial voltage shown in the second row corresponds to the final voltage of the previous measurement (first row). As can be seen from this table, the sensitivity decreases as the mid-point voltage decreases.

Figure 2 shows mid-point voltage vs. response curve. It shows the data points, regression line, and regression coefficient R². The closer the R² is to unity, the better is the fit to the data. Using the fitted equation, the response at a mid-point voltage can be calculated.

In the same way, measurements are performed for different positions of the alpha source, from which response at any mid-point voltage is determined for any position of the source. From the sum of the products of response at any source position and the ratio of the area of the annulus covered by the source to the total area of the chamber window, the response for a uniformly distributed source can be determined. Calibrations were performed for both types of chambers, chambers with and without Mylar window, electrets of three different thicknesses, and alpha particle sources of different energies and different source strengths.

³ Teflon is a registered trademark of duPont de Nemours and Co., Wilmington, DE 19898.

5.0 RESULTS AND DISCUSSION

Table 3 and Figure 2 show the response (change in voltage per disintegration) of an ST electret as a function of electret mid-point voltage. The response is higher at high voltages. The response decreases as the electret voltage decreases. This is because at low voltages, the velocity (product of ion mobility and the electric field) with which ions travel toward the electret for collection is small. These ions thus spend more time in the environment of ions of opposite polarity, resulting in increased loss of ions due to recombination. At high voltages, practically all ions are collected, and response reaches a nearly steady value (Knoll 1989).

Table 4 shows the response of an ST electret in 145-ml chamber when an alpha source is placed with its center at different distances from the chamber centerline. The response is determined at each position of the source. From these responses, the overall response is determined by summation of the products of the responses at different source positions and the ratios of the areas of the annular space corresponding to the source dimensions to the total area of the chamber window. At larger distances from the chamber centerline, the electret field is smaller, and loss of ions is greater. This table gives the response of the electret at any position of the source, as well as the response if the contamination were uniformly distributed over an area equal to or greater than the chamber opening (48.5 cm^2). Using the values of response at different mid-point voltages and noting the change in electret voltage per unit exposure time, surface alpha contamination can be determined.

As an example, assume an ST electret with an initial voltage of 425 V is loaded into a 145-ml windowless chamber and placed on a surface for measurement of its alpha contamination. Assume the final voltage of the electret, after exposure for 100 minutes, to be 375 V. The mid-point voltage is $(425 + 375)/2 = 400 \text{ V}$. Thus, there is a change of $425 - 375 = 50 \text{ V}$ in 100 min or 500 mV min^{-1} . Table 4 shows that at 400 V the response for a uniformly contaminated source is $0.7912 \text{ mV per disintegration}$. The change of 500 mV min^{-1} corresponds to a total contamination of $500/0.7912$ or 632 disintegrations per min. Since the chamber covers an area of 48.5 cm^2 , the contamination per unit area is $13.03 \text{ dpm cm}^{-2}$.

Table 5 shows the response of an ST electret in a 145-ml chamber for different alpha emitters placed in line with the chamber center. This table also shows the ratios of the response of the electret at a stated voltage to that at 750 V, as well as the average response and standard deviation of the average response at different voltages. As shown, the response is nearly constant and does not increase linearly with alpha particle energy. The reason for nearly constant response for the alpha emitters in the alpha energy range from 4.74 MeV (^{237}Np) to 5.79 MeV (^{244}Cm) is the average range of a 5 MeV alpha is about 35 mm in air. The chamber height is 34 mm. Therefore, the 4.74 MeV alpha particle from ^{237}Np expends all its energy within the chamber. In this distance, the high-energy alpha particles expend essentially the same energy in the air.

Table 6 shows the response of an ST electret in 960-ml chamber for ^{237}Np placed at different distances from the chamber centerline. Tables 7 through 9 present similar information about response for ^{239}Pu , ^{241}Am and ^{244}Cm , respectively. A comparison of Tables 4 and 5 with Tables 8 and 9 shows that for higher-energy alpha emitters, the response at high voltages is higher for 960-ml chamber than that for 145-ml when the sources are placed in line with chamber centerline. This is because in a large chamber (hemisphere: radius 76.5 mm) even high-energy alpha particles expend their entire energy in air. Therefore, higher-energy alphas show higher

response per disintegration basis in 960-ml chamber than in 145-ml chamber. Further, as the voltage on the electret decreases, the response of 960-ml chamber decreases particularly at about 100 V. Its use, therefore, is recommended for mid-point voltages of 200 V and above. For uniformly distributed sources, the response of a 960-ml chamber per disintegration is slightly lower than that of a 145-ml chamber. This is because ions produced by alpha contamination located at larger distances from the chamber centerline are farther away from the electret surface in 960-ml chamber than they are in 145-ml chamber. With the result, electric fields are lower, and hence, loss of ions due to recombination is higher.

Table 8 shows that for uniformly distributed activity, the response at a mid-point voltage of 500 V is $0.775 \text{ mV disintegration}^{-1}$. Assume an electret with an initial voltage of 525 V was exposed for 100 minutes to a uniform contamination, and its voltage reduces to 475 V. There is voltage drop of 50 V in 100 minutes or 500 mV min^{-1} . This voltage loss rate corresponds to a total contamination of $500/0.775 = 645 \text{ dpm}$ or $645/180 = 3.58 \text{ dpm cm}^{-2}$, since 960-ml chambers measure contamination from 180 cm^2 of surface. The 145-ml chamber, as noted earlier, produces the same drop in voltage for the same exposure period when the contamination level is $13.03 \text{ dpm cm}^{-2}$. Thus, an electret in 960-ml chamber produces higher response by a factor of $13.03/3.58 = 3.65$ than in 145-ml chamber, so an electret in 960-ml chamber can measure the same contamination in a shorter time (by a factor of 3.65) than in 145-ml chamber. The 50 V drop corresponds to nearly 64,000 disintegrations or $640 \text{ disintegration min}^{-1}$ for a 100 min exposure. Under these exposure conditions the measurement uncertainty will be governed mainly by the calibration uncertainty of nearly 10% (Table 12) since the voltage measurement uncertainty, assuming an error of 1 V in initial voltage and 1 V in final voltage measurement, will be only $\sqrt{2}/50$ or 2.8% (Meyer et al. 1994). The time measurement uncertainty will be negligible. Following Meyer et al. (1994) for 50% voltage measurement uncertainty ($\sqrt{2} \text{ V}$ due to initial and final voltage reading in a drop of 3 volts due to exposure) the method minimum detection limit is 4000 disintegrations.

Tables 10 and 11 show the response of an ST electret in 960-ml chamber with aluminized Mylar window for ^{237}Np and ^{241}Am , respectively. A comparison of Table 6 with Table 10 and Table 8 with Table 11 shows that the response decreases when the chamber window is covered with Mylar of thickness 0.8 mg cm^{-2} . This is expected since the alpha particles lose energy in passing through Mylar and produce fewer ion pairs than they do without Mylar.

Table 12 shows the response of an ST electret in 960-ml windowless chamber exposed to uniformly distributed sources of ^{237}Np , ^{239}Pu , ^{241}Am , and ^{244}Cm . This table also exhibits the average and standard deviation of the response for these sources. If the average response value is used for an unknown alpha emitter in the energy range 4.74 MeV to 5.79 MeV, the measurement uncertainty will be less than 10%. That is adequate for a field contamination measurement instrument. Table 12 also displays the average of the responses (Table 10 and Table 11) for uniformly distributed sources when the chamber window is covered with aluminized Mylar. This table also presents the ratio of the response of the EIC without and with Mylar window. The response decreases to nearly one-half of its value when a Mylar window is used. The lower value of response will require higher exposure time, for a given contamination level, to produce a desired electret voltage change. The use of a Mylar window is recommended, as it prevents the contamination of the chamber from removable contamination and it also eliminates the interference of surface electrostatic charges on ion collection. The thickness of Mylar should be less than the range of the alpha particle or the alpha particle will be absorbed within the window.

For uniformly distributed sources Fig. 3 shows a summary of the responses (of ^{241}Am in 145-ml chamber without window; of ^{241}Am in 960-ml chamber without window; average of ^{237}Np , ^{239}Pu , ^{241}Am , and ^{244}Cm in 960-ml chamber without window, and average of ^{237}Np and ^{241}Am in 960-ml chamber with an aluminized Mylar window).

The response of electrets of different thicknesses in 145-ml chamber was determined. The response increases as the electret thickness increases. An ST electret (thickness: 1.524 mm) is observed to be nearly 12 times (11.73 ± 0.58) more sensitive than an LT electret (thickness: 0.127 mm). A sensitive electret (thickness: 4.572 mm) exhibits nearly 2.4 times (2.39 ± 0.09) higher sensitivity than an ST electret.

The foregoing study was carried out using alpha calibration sources of radioactivity varying from 243.5 Bq to 398.3 Bq. At high contamination levels, the ion pair density will be large, which may lead to increased ion loss due to recombination. Experiments were therefore carried out for ^{241}Am alpha sources of radioactivity ranging from 243.5 Bq to 17490 Bq to determine the effect of high activity on EIC. LT electrets were used for this study, since the small (~ 10 s) exposure times needed with ST electrets will result in higher exposure-time measurement errors. Electrets with high initial voltage (>1000 V) were used for efficient ion collection. Responses of LT electrets were determined in 145-ml and 960-ml chambers. Since at high electret voltages practically all ions were collected and response was nearly the same at all source strengths, ratio of response at any mid-point voltage to that at 1000 V was obtained and is shown in Table 13. Columns two through four show the ratio of the response for different sources for 145-ml chamber, and columns five through seven show the ratio for 960-ml chamber. It is observed that at low mid-point voltages, this ratio is lower at high-source radioactivity than at low radioactivity. This effect is seen clearly for 960-ml chamber. In 960-ml chamber at mid-point voltage of 200 V, only 40.6% of the ions are collected by the electret at an activity of 17490 Bq as against 72.4% collected at 243.5 Bq, suggesting increased loss of ions at high ion densities due to recombination. Since the ratio of the response at any voltage, particularly at low voltages, is different at high radioactivity and low radioactivity, the calibration performed at low radioactivity does not hold true for the high contamination level when electret voltage is low. With the 960-ml chamber, if the calibration is performed at 243.5 Bq and measurements are performed (in the mid-point voltage range 750 to 200 V) at high contamination levels, the estimated contamination will be lower than the actual by 3 to 44%, depending on contamination level and mid-point voltage. For the same conditions, the estimated values in a 145-ml chamber will be lower by 2 to 21%. The smaller collection (or increased loss) of ions in a 960-ml chamber than in a 145-ml chamber is because of lower electric fields in the bigger chamber for a given voltage on the electret. The lower electric field produces lower ion velocity (velocity is a product of electric field and ion electrical mobility) for being swept toward the electret. Because of lower velocity, ions spend more time in the atmosphere of ions of opposite polarity, resulting in increased probability of recombination.

The EICs used for measurement of surface alpha contamination respond to any radiation as long as it is able to enter the chamber volume and create ions there. One of the methods of accounting for contributions of other radiations is to make two measurements; one with an aluminized Mylar window and the other with a carbon-coated Tyvek⁴ window of 7 mg cm^{-2} thickness. The former

⁴ Tyvek is a registered trademark of duPont de Nemours and Co., Wilmington, DE 19898.

measures contributions from alpha, beta, gamma, and radon (radon diffuses into the chamber through spaces between the electret mounting thread in the chamber and through the Tyvek window). The measurement with Tyvek gives voltage drop due to all these radiations except alpha. The difference between the two readings provides a measure of alpha contamination. Alternatively, if beta contamination is negligible and if gamma and radon levels are known, their contribution can be calculated and subtracted from the measured values to arrive at the alpha contamination levels. Columns eight through eleven of Table 13 show the response of an ST electret in 145-ml and 960-ml chambers for a gamma radiation background⁵ (E-PERM 1996) exposure rate of $2.58 \times 10^{-9} \text{ C kg}^{-1} (10 \mu\text{R h}^{-1})$ and radon concentration⁶ (E-PERM 1994) of $37 \text{ Bq m}^{-3} (1 \text{ pCi l}^{-1})$. Using this table, the response for any radiation level or radon concentration can be determined.

The commercially available EICs consist of two chambers and three electret types (Table 1), which gives six chamber-electret combinations. The 145-ml chamber is used in the mid-point voltage range 100 to 750 V. DOE Methods Compendium Protocol (Meyer et al. 1994) has recommended an electret voltage of 400 V for normalizing response of a 145-ml chamber. DOE paper also contains information about the response for different alpha sources, source dimensions, for the effect of Mylar, and about measurement uncertainty. Table 14 presents a summary of main results. This table shows response of a 145-ml chamber at 400 V. It also shows response of an ST electret in 960-ml chamber at 500 V. 500 V was chosen because a 960-ml chamber is recommended for use in the voltage range 200 V to 750 or higher, and the voltage corresponding to average response works out close to 500 V. Table 14 also gives the time required for an electret voltage drop of 15 V when the 145-ml chamber (window area: 48.5 cm^2) and 960-ml chamber (window area: 180 cm^2) are exposed to free release level (Shleien et al. 1998) uniform alpha contamination of 1 dpm cm^{-2} . A 15 V drop can be measured with a voltage measurement uncertainty of 10%. For a 15 V drop, an ST electret in 145-ml needs to be exposed for 391 minutes. The exposure times for LT and sensitive electrets for the same voltage are 76 hours and 164 minutes, respectively. For the same voltage drop of 15 V in a 960-ml chamber, the times required for LT, ST, and sensitive electrets are 19 hours, 108 minutes, and 44 minutes, respectively. Table 14 also presents the useful range of the EICs. The useful range is given in terms of disintegrations to which the chambers are exposed so that voltage drops from 750 V to 100 V for 145-ml chamber or from 750 V to 200 V for 960-ml chamber. Thus, an ST electret in a 145-ml chamber can measure nearly 8×10^5 disintegrations. A 960-ml chamber can be used for measurement of 7×10^5 disintegrations. The measurement values will be higher by a factor of 11.7 for an LT electret and lower by a factor of 2.4 for the sensitive electret. For high contamination levels, an LT electret in 145-ml should be used. At low contamination levels, a 960-ml chamber with either ST or sensitive electret can be used depending on the measurement time available and the accuracy desired. When a Mylar window is used, the exposure times needed, as well as measurement range, will be higher by a factor of nearly 2 compared with the case of windowless chambers.

⁵ E-PERM System Manual Part II.17 X-Rays. 26 July, 1996. E-PERM is a trademark of a patented product manufactured by Rad Elec, Inc., 5714-C Industry Lane, Frederick, MD 21701.

⁶ E-PERM System Manual Part I. Appendix-I, Rev. #1 10 November, 1994. E-PERM is a trademark of a patented product manufactured by Rad Elec, Inc., 5714-C Industry Lane, Frederick, MD 21701.

Table 14 shows that a drop of 15 V occurs in an ST electret at a mid-point voltage of 400 V in a 145-ml chamber when the EIC is exposed to an alpha contamination of 1 dpm cm⁻² for 391 minutes. Using values in Table 13, one can determine the radon concentrations and gamma radiation levels that will produce the same effect (the same voltage drop in the same time). For example, a radon concentration of 2740 Bq m⁻³ (74 pCi l⁻¹) or a gamma radiation field of 2.8×10^{-7} C kg⁻¹ (1.1 mR h⁻¹) is equivalent to an alpha contamination of 1 dpm cm⁻² for the 145-ml chamber. For a 960-ml chamber, a radon concentration of 777 Bq m⁻³ (21 pCi l⁻¹) or a gamma radiation level of 1.1×10^{-7} C kg⁻¹ (0.43 mR h⁻¹) is equivalent to the same alpha contamination that produces a 15 V drop in an ST electret in 108 minutes.

6.0 CONCLUSIONS

A suitable combination of electret ion chambers and electret types, depending upon the time available for measurement and the desired measurement accuracy, can be used for measurement of surface alpha contamination. With about 10% voltage measurement (or 15% total) uncertainty, an alpha contamination at the level of free release (1 dpm cm^{-2} from transuranics) can be measured with a 145-ml chamber in 76, 6.5, or 2.7 hours depending upon the type of electret (LT, ST, or sensitive) used. Using a 960-ml chamber and similar electrets, the same contamination can be measured in 19, 1.8, and 0.75 hours, respectively. The measurement times will be nearly double when a Mylar window is used. A large number of EICs can be deployed simultaneously for about an hour or overnight or over a weekend, depending on chamber-electret combination, to measure surface contamination in any large facility. EICs are light-weight and can be easily placed on different surfaces, such as floors, walls, and ceilings, for alpha contamination measurement. An electret can be used many times before its charge drops to a low value that necessitates its replacement with a new electret.

In addition to surface alpha contamination, EICs also respond to radon in the atmosphere and gamma radiation. This study presents the contribution that these radiations make on the electret voltage change. When this contribution is subtracted from the total electret voltage change, alpha contamination in the presence of radon and gamma can be determined. An EIC calibrated at low radioactivity should be used at high mid-point voltages for measurement of high contamination levels to reduce measurement errors.

7.0 ACCOMPLISHMENTS

An electret ion chamber (EIC) system consisting of an electret loaded in an ionization chamber has been calibrated for measurement of alpha contamination on surfaces (floors, walls and ceilings). The response of the system was determined for different voltages on electret and for different positions of the source (localized and uniformly distributed) at the chamber base. Four alpha emitting radionuclides (^{237}Np , ^{239}Pu , ^{241}Am , and ^{244}Cm) of different alpha energies (4.74 MeV to 5.79 MeV) were used. The response of the EIC was determined for these sources to arrive at the measurement uncertainty for an alpha source of unknown energy. Influence of high contamination on response of the EIC was determined, and suggestions for the necessary care to be taken were made. Electrets of three different thicknesses and chambers of two sizes are commercially available. Thus, a combination of six EICs can be made. The exposure times needed with different EICs for a given contamination measurement as well as useful range of the EICs were determined. Use of a Mylar window, which reduces the sensitivity to nearly one-half and doubles the useful range, was recommended to overcome the interference of any electrostatic charge on surfaces.

A paper on surface alpha contamination measurement has been submitted to Health Physics Journal (Dua et al. 1998).

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Figure.1. Electret ion chamber system showing a charge reader, a 960-ml chamber, a 145-ml chamber, and an ST electret.

Figure 2. Response of ST electret in 145-ml chamber to 243.5 Bq ^{241}Am source at various mid-point voltages.

Figure 3. Response of ST electret for uniformly distributed sources.

- (1) ^{241}Am in 145-ml chamber without window
- (2) ^{241}Am in 960-ml chamber without window
- (3) Average of ^{237}Np , ^{239}Pu , ^{241}Am , and ^{244}Cm in 960-ml chamber without window
- (4) Average of ^{237}Np and ^{241}Am in 960-ml chamber with an aluminized Mylar window.

Table 1.
Properties of the electret ion chambers

Component of EIC	Properties		
	Material	Entrance window area	Dimensions
Chamber volume: 145 mL	Carbon-filled polypropylene	48.5 cm ²	Cylinder diameter: 185 mm Height: 38 mm
Chamber volume: 960 mL	Carbon-filled polypropylene	180 cm ²	Hemisphere diameter: 153 mm Electret loaded at the curved surface
Electret (LT)	Teflon	-	Thickness: 0.127 mm Diameter: 34 mm
Electret (ST)	Teflon	-	Thickness: 1.524 mm Diameter: 34 mm
Electret (Sensitive)	Teflon	-	Thickness: 4.572 mm Diameter: 34 mm

Table 2.
Alpha-particle sources and their characteristics

Alpha source	Weighted alpha- particle energy* (MeV)	Active diameter (mm)	Alpha radioactivity (Bq)	Standard deviation (%)	Supplier
²³⁷ Np	4.74	19	283.3	5.0	The Source, Inc.
²³⁹ Pu	5.09	19	398.3	5.0	
²⁴⁴ Cm	5.79	19	341.7	5.0	
²⁴¹ Am	5.47	5 - 12.5	243.5	3.0	Isotope
²⁴¹ Am	5.47	5 - 12.5	6386.0	3.0	Products
²⁴¹ Am	5.47	5 - 12.5	17490.0	3.0	Laboratories

* Meyer et al. 1994

Table 3.
Response of ST electret in 145-ml chamber; 243.5 Bq ²⁴¹Am source placed with its center aligned with chamber centerline

Initial voltage (V)	Final voltage (V)	Voltage change (V)	Exposure time (s)	Source activity (Bq)	Disintegrations (time in s x activity in Bq) (disintegrations)	Mid point voltage (V)	Response (mV disintegration ⁻¹)
710	675	35	120	243.5	29220	692.5	1.1978
675	640	35	120	243.5	29220	657.5	1.1978
640	607	33	120	243.5	29220	623.5	1.1294
607	574	33	120	243.5	29220	590.5	1.1294
574	541	33	120	243.5	29220	557.5	1.1294
541	509	32	120	243.5	29220	525.0	1.0951
509	476	33	120	243.5	29220	492.5	1.1294
476	444	32	120	243.5	29220	460.0	1.0951
444	413	31	120	243.5	29220	428.5	1.0609
413	382	31	120	243.5	29220	397.5	1.0609
382	343	39	150	243.5	36525	362.5	1.0678
343	298	45	180	243.5	43830	320.5	1.0267
298	269	29	120	243.5	29220	283.5	0.9925
269	240	29	120	243.5	29220	254.5	0.9925
240	211	29	120	243.5	29220	225.5	0.9925
211	179	32	150	243.5	36525	195.0	0.8761
179	147	32	150	243.5	36525	163.0	0.8761
147	117	30	150	243.5	36525	132.0	0.8214

Table 4.
Response of ST electret in 145-ml chamber; 243.5 Bq ^{241}Am source at different distances from chamber centerline and uniformly distributed to the size of the chamber opening

^{241}Am : Response of windowless chamber (mV disintegration ⁻¹)					
MPV (V)	Source - chamber center distance (mm)				Source uniformly distributed
	0	12.5	25	35	
700	1.1978	1.1509	0.9283	0.6236	0.8751
650	1.1870	1.1411	0.9194	0.6154	0.8662
600	1.1753	1.1273	0.9034	0.5978	0.8502
550	1.1627	1.1146	0.8908	0.5851	0.8376
500	1.1488	1.1007	0.8769	0.5713	0.8237
450	1.1334	1.0854	0.8615	0.5559	0.8083
400	1.1163	1.0682	0.8444	0.5387	0.7912
350	1.0968	1.0476	0.8226	0.5160	0.7694
300	1.0743	1.0251	0.8001	0.4935	0.7469
250	1.0478	0.9986	0.7736	0.4670	0.7204
200	1.0153	0.9649	0.7387	0.4312	0.6855
150	0.9735	0.9377	0.7555	0.5042	0.7112
100	0.9144	0.8775	0.6941	0.4419	0.6498

Table 5.
Response of ST electret in 145-ml chamber for different sources; source centers aligned with chamber centerline

Mid-point voltage (V)	Response (mV disintegration ⁻¹)				Ratio of response at the stated voltage to that at 750 V				Average response ratio	Standard deviation of response ratio
	²⁴¹ Am	²³⁷ Np	²³⁹ Pu	²⁴⁴ Cm	²⁴¹ Am	²³⁷ Np	²³⁹ Pu	²⁴⁴ Cm	All Sources	All Sources
750	1.1978	1.2530	1.2790	1.2196	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000
700	1.1833	1.2409	1.2692	1.2088	0.9879	0.9903	0.9923	0.9912	0.9904	0.0019
650	1.1678	1.2279	1.2587	1.1973	0.9750	0.9800	0.9841	0.9817	0.9802	0.0039
600	1.1510	1.2139	1.2473	1.1848	0.9610	0.9688	0.9752	0.9714	0.9691	0.0060
550	1.1328	1.1987	1.2350	1.1712	0.9457	0.9566	0.9656	0.9603	0.9571	0.0084
500	1.1128	1.1819	1.2214	1.1563	0.9291	0.9433	0.9550	0.9481	0.9439	0.0110
450	1.0908	1.1635	1.2065	1.1398	0.9106	0.9285	0.9433	0.9346	0.9293	0.0138
400	1.0661	1.1428	1.1898	1.1215	0.8900	0.9120	0.9302	0.9195	0.9130	0.0170
350	1.0381	1.1194	1.1708	1.1006	0.8667	0.8934	0.9154	0.9024	0.8945	0.0206
300	1.0058	1.0924	1.1489	1.0765	0.8397	0.8718	0.8983	0.8827	0.8731	0.0248
250	0.9676	1.0604	1.1230	1.0481	0.8078	0.8463	0.8780	0.8594	0.8479	0.0297
200	0.9208	1.0213	1.0913	1.0132	0.7688	0.8151	0.8532	0.8308	0.8170	0.0357
150	0.8606	0.9708	1.0505	0.9683	0.7185	0.7748	0.8213	0.7940	0.7771	0.0435
100	0.7756	0.8998	0.9929	0.9050	0.6475	0.7181	0.7763	0.7421	0.7210	0.0545

Table 6.
Response of ST electret in 960-ml windowless chamber; 283.3 Bq ^{237}Np source placed at different distances from chamber centerline and uniformly distributed (to the size of chamber opening)

^{237}Np : Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)						
MPV (V)	Source-chamber centerline distances					Source uniformly distributed
	0 mm	13.75 mm	27.5 mm	46.5 mm	65.5 mm	
750	1.1715	1.1286	1.0864	0.9716	0.5056	0.7964
700	1.1557	1.1286	1.0714	0.9512	0.4917	0.7808
650	1.1386	1.0961	1.0552	0.9294	0.4767	0.7627
600	1.1202	1.0779	1.0377	0.9057	0.4606	0.7439
550	1.1002	1.0582	1.0187	0.8800	0.4431	0.7234
500	1.0783	1.0365	0.9978	0.8519	0.4239	0.7009
450	1.0540	1.0126	0.9748	0.8208	0.4027	0.6761
400	1.0269	0.9859	0.9491	0.7860	0.3790	0.6484
350	0.9962	0.9556	0.9199	0.7466	0.3521	0.6169
300	0.9608	0.9206	0.8862	0.7011	0.3210	0.5806
250	0.9188	0.8792	0.8464	0.6472	0.2843	0.5376
200	0.8675	0.8286	0.7976	0.5813	0.2394	0.4851

Table 7.
Response of ST electret in 960-ml windowless chamber; 398.3 Bq ^{239}Pu source placed at different distances from chamber centerline and uniformly distributed (to the size of chamber opening)

^{239}Pu : Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)						
MPV (V)	Source-chamber centerline distances					Source uniformly distributed
	0 mm	12.75 mm	25.5 mm	46.5 mm	62.5 mm	
750	1.2563	1.2362	1.2166	1.0057	0.5215	0.8442
700	1.2415	1.2192	1.1998	0.9842	0.5090	0.8279
650	1.2257	1.2008	1.1818	0.9612	0.4955	0.8103
600	1.2085	1.1811	1.1624	0.9362	0.4809	0.7913
550	1.1899	1.1596	1.1412	0.9092	0.4651	0.7707
500	1.1696	1.1360	1.1180	0.8795	0.4477	0.7481
450	1.1470	1.1100	1.0924	0.8467	0.4285	0.7231
400	1.1218	1.0809	1.0638	0.8100	0.4071	0.6951
350	1.0933	1.0479	1.0313	0.7684	0.3828	0.6635
300	1.0603	1.0098	0.9938	0.7204	0.3548	0.6269
250	1.0213	0.9648	0.9495	0.6637	0.3216	0.5836
200	0.9736	0.9096	0.8952	0.5942	0.2810	0.5307

Table 8.
Response of ST electret in 960-ml windowless chamber;
 $243.5 \text{ Bq } ^{241}\text{Am}$ source placed at different distances from chamber
centerline and uniformly distributed (to the size of chamber opening)

Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)							
MPV (V)	Source-chamber centerline distances						Source uniformly distributed
	0 mm	15 mm	30 mm	45 mm	60 mm	70 mm	
750	1.3057	1.2755	1.2454	1.0994	0.6767	0.5972	0.8816
700	1.2914	1.2610	1.2283	1.0773	0.6581	0.5817	0.8639
650	1.2762	1.2453	1.2099	1.0535	0.6382	0.5651	0.8449
600	1.2597	1.2285	1.1900	1.0279	0.6167	0.5471	0.8243
550	1.2417	1.2101	1.1684	1.0000	0.5934	0.5276	0.8019
500	1.2220	1.1900	1.1448	0.9694	0.5678	0.5062	0.7775
450	1.2003	1.1677	1.1186	0.9356	0.5395	0.4826	0.7504
400	1.1760	1.1429	1.0894	0.8978	0.5079	0.4561	0.7202
350	1.1485	1.1147	1.0563	0.8550	0.4720	0.4262	0.6859
300	1.1167	1.0822	1.0180	0.8056	0.4306	0.3916	0.6463
250	1.0791	1.0437	0.9728	0.7471	0.3817	0.3506	0.5994
200	1.0331	0.9966	0.9174	0.6755	0.3217	0.3006	0.5421
150	0.9737	0.9359	0.8460	0.5833	0.2445	0.2360	0.4682
100	0.8901	0.8503	0.7454	0.4532	0.1356	0.1450	0.3641

Table 9.
Response of ST electret in 960-ml windowless chamber;
341.7 Bq ^{244}Cm source placed at different distances from chamber
centerline and uniformly distributed (to the size of chamber opening)

^{244}Cm : Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)						
MPV (V)	Source-chamber centerline distances					Source uniformly distributed
	0 mm	13.75 mm	27.5 mm	46.5 mm	65.5 mm	
750	1.4457	1.3740	1.3385	1.1705	0.6551	0.9865
700	1.4288	1.3551	1.3201	1.1473	0.6395	0.9679
650	1.4106	1.3348	1.3004	1.1224	0.6228	0.9479
600	1.3910	1.3129	1.2790	1.0955	0.6047	0.9262
550	1.3696	1.2891	1.2558	1.0663	0.5851	0.9027
500	1.3463	1.2630	1.2304	1.0343	0.5636	0.8770
450	1.3205	1.2341	1.2023	0.9989	0.5398	0.8485
400	1.2916	1.2019	1.1709	0.9593	0.5132	0.8166
350	1.2588	1.1654	1.1353	0.9144	0.4831	0.7806
300	1.2210	1.1232	1.0942	0.8626	0.4483	0.7389
250	1.1763	1.0733	1.0456	0.8014	0.4072	0.6896
200	1.1216	1.0122	0.9861	0.7264	0.3568	0.6293

Table 10.
Response of ST electret in 960-ml Mylar-window chamber;
283.3 Bq ^{237}Np source placed at different distances from chamber
centerline and uniformly distributed (to the size of chamber opening)

^{237}Np : Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)						
MPV (V)	Source-chamber centerline distances					Source uniformly distributed
	0 mm	13.75 mm	27.5 mm	46.5 mm	65.5 mm	
750	0.5756	0.5497	0.5385	0.5080	0.3257	0.4358
700	0.5661	0.5433	0.5316	0.4984	0.3150	0.4263
650	0.5559	0.5364	0.5242	0.4880	0.3034	0.4161
600	0.5449	0.5289	0.5162	0.4768	0.2909	0.4051
550	0.5330	0.5208	0.5075	0.4646	0.2774	0.3932
500	0.5199	0.5119	0.4980	0.4513	0.2625	0.3800
450	0.5054	0.5021	0.4875	0.4366	0.2460	0.3655
400	0.4893	0.4911	0.4757	0.4201	0.2277	0.3493
350	0.4709	0.4787	0.4624	0.4014	0.2068	0.3310
300	0.4498	0.4644	0.4470	0.3798	0.1828	0.3098
250	0.4247	0.4474	0.4289	0.3543	0.1543	0.2847
200	0.3941	0.4266	0.4066	0.3231	0.1195	0.2540

Table 11.
Response of ST electret in 960-ml Mylar-window chamber; 243.5 Bq ^{241}Am source at different distances from chamber centerline and uniformly distributed (to the size of the chamber opening)

^{241}Am : Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)							
MPV (V)	Source-chamber centerline distances						Source uniformly distributed
	0 mm	15 mm	30 mm	45 mm	60 mm	65.75 mm	
750	0.7211	0.6474	0.6124	0.6734	0.4261	0.2913	0.4821
700	0.7075	0.6376	0.6029	0.6597	0.4088	0.2836	0.4708
650	0.6930	0.6271	0.5927	0.6449	0.3901	0.2754	0.4587
600	0.6773	0.6158	0.5817	0.6290	0.3700	0.2665	0.4456
550	0.6603	0.6034	0.5697	0.6117	0.3481	0.2568	0.4313
500	0.6416	0.5899	0.5566	0.5927	0.3241	0.2463	0.4157
450	0.6210	0.5749	0.5421	0.5717	0.2976	0.2346	0.3985
400	0.5979	0.5582	0.5259	0.5483	0.2680	0.2215	0.3792
350	0.5717	0.5393	0.5075	0.5217	0.2344	0.2067	0.3573
300	0.5415	0.5174	0.4863	0.4910	0.1956	0.1896	0.3321
250	0.5058	0.4915	0.4613	0.4547	0.1498	0.1693	0.3022
200	0.4621	0.4599	0.4306	0.4103	0.0937	0.1445	0.2657

Table 12.
Response of ST electret in 960-ml chamber for different
uniformly distributed sources with and without Mylar window

Response (change in electret voltage per disintegration) (mV disintegration ⁻¹)								
MPV (V)	No Mylar						Mylar	Ratio
	²³⁷ Np	²³⁹ Pu	²⁴¹ Am	²⁴⁴ Cm	Average	SD	Average	No Mylar/Mylar
750	0.7964	0.8442	0.8816	0.9865	0.8772	0.0808	0.4590	1.9113
700	0.7808	0.8279	0.8639	0.9679	0.8601	0.0795	0.4486	1.9175
650	0.7627	0.8103	0.8449	0.9479	0.8414	0.0785	0.4374	1.9237
600	0.7439	0.7913	0.8243	0.9262	0.8214	0.0773	0.4253	1.9312
550	0.7234	0.7707	0.8019	0.9027	0.7997	0.0759	0.4122	1.9399
500	0.7009	0.7481	0.7775	0.8770	0.7759	0.0744	0.3979	1.9500
450	0.6761	0.7231	0.7504	0.8485	0.7495	0.0728	0.3820	1.9621
400	0.6484	0.6951	0.7202	0.8166	0.7201	0.0709	0.3643	1.9768
350	0.6169	0.6635	0.6859	0.7806	0.6867	0.0689	0.3441	1.9954
300	0.5806	0.6269	0.6463	0.7389	0.6482	0.0665	0.3209	2.0197
250	0.5376	0.5836	0.5994	0.6896	0.6026	0.0637	0.2934	2.0535
200	0.4851	0.5307	0.5421	0.6293	0.5468	0.0603	0.2598	2.1045
							Average	1.9619
							Standard deviation (SD)	0.0454

Table 13.
Response of electrets in 145-ml and 960-ml chambers for ^{241}Am
alpha sources of different source strengths and gamma radiation and radon

Responses of LT electrets obtained by exposing the electrets in 145-ml and 960-ml chambers to alpha sources of different strengths. Ratio of the responses for different alpha activities at the stated voltage to that at 1000 V							Change in volts per hour when an ST electret in 145-ml and 960-ml chambers is exposed to radon concentration (37 Bq m^{-3}) or gamma radiation level ($2.58 \times 10^{-9} \text{ Ckg}^{-1}$)			
MPV (V)	145-ml chamber			960-ml chamber			145-ml chamber		960-ml chamber	
	243.5 Bq	6386 Bq	17490 Bq	243.5 Bq	6386 Bq	17490 Bq	Radon	Gamma	Radon	Gamma
1000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000				
950	0.9947	0.9911	0.9890	0.9912	0.9846	0.9811				
900	0.9891	0.9817	0.9774	0.9819	0.9684	0.9611				
850	0.9832	0.9718	0.9651	0.9721	0.9513	0.9400				
800	0.9769	0.9613	0.9521	0.9617	0.9331	0.9176				
750	0.9703	0.9501	0.9382	0.9507	0.9138	0.8938	0.0643	0.0437	0.4381	0.2582
700	0.9632	0.9382	0.9234	0.9389	0.8931	0.8684	0.0634	0.0431	0.4292	0.2456
650	0.9555	0.9253	0.9075	0.9262	0.8709	0.8410	0.0626	0.0426	0.4202	0.2330
600	0.9472	0.9114	0.8903	0.9124	0.8469	0.8115	0.0617	0.0420	0.4113	0.2203
550	0.9382	0.8964	0.8716	0.8975	0.8209	0.7793	0.0608	0.0415	0.4024	0.2077
500	0.9283	0.8798	0.8511	0.8812	0.7923	0.7442	0.0600	0.0409	0.3934	0.1951
450	0.9174	0.8616	0.8285	0.8631	0.7608	0.7053	0.0591	0.0403	0.3845	0.1825
400	0.9052	0.8412	0.8032	0.8429	0.7255	0.6618	0.0582	0.0398	0.3755	0.1699
350	0.8914	0.8180	0.7745	0.8200	0.6855	0.6125	0.0574	0.0392	0.3666	0.1572
300	0.8755	0.7913	0.7414	0.7936	0.6393	0.5556	0.0565	0.0387	0.3576	0.1446
250	0.8566	0.7597	0.7022	0.7624	0.5846	0.4883	0.0556	0.0381	0.3487	0.1320
200	0.8336	0.7210	0.6543	0.7241	0.5178	0.4060	0.0548	0.0376	0.3398	0.1194
150	0.8038	0.6711	0.5925				0.0539	0.0370	0.3308	0.1067
100	0.7619	0.6008	0.5054				0.0530	0.0365	0.3219	0.0941

Table 14.
Summary of results

Source	145-ml chamber			960-ml chamber		
	Response	Exposure time for 15 V change at surface contamination of 1 dpm cm ⁻²	Useful range of electret	Response	Exposure time for 15 V change at surface contamination of 1 dpm cm ⁻²	Useful range of electret
	(mV dis. ⁻¹)	(minutes)	(dis.)	(mV dis. ⁻¹)	(minutes)	(dis.)
²³⁷ Np (No Mylar)	—	—	—	0.7009	119	784675
²³⁹ Pu (No Mylar)	—	—	—	0.7481	111	735231
²⁴¹ Am (No Mylar)	0.7912	391	821537	0.7775	107	707425
²⁴⁴ Cm (No Mylar)	—	—	—	0.8770	95	627174
Average				0.7759	108	713626
Standard deviation				0.0744	10	65897
²³⁷ Np (Mylar)	—	—	—	0.3800	219	1447194
²⁴¹ Am (Mylar)	—	—	—	0.4157	200	1323059
Average				0.3979	210	1385127
Standard deviation				0.0126	6.6	43888

dis. = disintegration