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Charge Transport and Storage in the Radiation-Charged Electret Ionization Chamber

by

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January, 1994

A Thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements of the degree of
Doctor of Philosophy

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Charge transport in the radiation-charged electret ionization chamber
Abstract

Numerical calculations of time-dependent charge distributions are presented and compared with distributions measured on radiation-charged electrets made of thin polymer films, which are charged and discharged in a Radiation-Charged Electret Ionization Chamber (REIC) through the application of ionizing radiation. The chamber resembles a parallel plate ionization chamber, and has a thin film of polymer covering the collector and guard-ring electrodes. Calculations are performed by solving Laplace’s Equation for the true geometry of the charging/discharging set-up, then applying estimates of ion-density distributions generated from known scattering distributions and/or simpler approximations. Measurements of radiation induced conductivity (RIC) are presented and fitted to an empirically derived analytical model, and the effects of RIC on the operation of a radiation dosimeter based on the electret are investigated and discussed. Short-term and long-term charge decay from the electret is measured and fitted to a previously developed model. The effects of post-charging heat treatment of the radiation-charged electret are presented and discussed. Lastly, the dosimetric characteristics of the REIC are considered in light of those physical aspects investigated here.
Résumé

Les calculs numériques des distributions de charge variables dans le temps sont présentés et comparés à la distribution de charge mesurée sur des électrets faits de minces films de polymer chargés par irradiation. Ces derniers sont chargés et déchargés dans une chambre d'ionisation à électret radiochargé par radiation ionisante. La chambre ressemble à une chambre d'ionisation à électrodes parallèles mais un mince film de polymer recouvre l'électrode collectrice. Les calculs sont effectués en solutionnant les équations de Laplace pour la géométrie représentant le dispositif de charge-décharge puis en appliquant les estimations des distributions de densité ionique générées par les distributions connues de diffusion ou par des approximations simples. Les mesures de la conductivité radio-induite (CRI) sont présentées et ajustées à un modèle analytique empirique. Les effets de la CRI sur le fonctionnement d'un dosimètre basé sur l'électret sont examinés et discutés. La décroissance à court terme de la charge de l'électret est mesurée et utilisée dans la mesure de la CRI. La décroissance de la charge à long terme est également mesurée et ajustée à un modèle développé antérieurement.
Original Contribution

Findings are presented from investigations of thin-film polymer electrets, charged in an ionization chamber by exposure to X or γ radiation, a technique labeled radiation-charging. Charge distributions on radiation-charged electrets are generated through a numerical model that solves Laplace’s Equation for the true charging geometry and boundary conditions, and uses the results of these calculations in conjunction with estimates of the radiation induced ion-density to predict the location of charge deposition.

Charge distributions on the electret are measured in two dimensions, and the information is converted to one dimension by using statistical methods to find the true origin of the cylindrical co-ordinate system and averaging over the angular co-ordinate. The calculated and measured charge distributions are compared, and found to be in close agreement during both charging and discharging cycles.

Radiation induced conductivity (RIC) in the electret is modelled by a set of empirical equations which fit measured values very well. An expression which accounts for the flow of charge generated by RIC during charging and discharging of the radiation-charged electret is then incorporated into a previously published expression describing the charging and discharging currents in the charging chamber. It is shown that the current generated by RIC is not measured during the charging or discharging though it increases the time needed for charging and decreases the time needed for discharging. It is then shown that it is possible for the dose rate dependence of RIC to adversely affect the use of the electret in dosimetry by making its response dose rate-dependent, though the effect is far more pronounced if the duration of the individual doses which make up the total dose is very short.

Measurements of both short and long-term loss of electrostatic charge are
presented. This natural or dark decay is shown to agree well with a model proposed previously for the migration of charge through corona-charged electretcs. It is shown that there is a degree of invariance of decay patterns over different time scales.
Acknowledgements

It is my honour to thank my supervisor, Dr. B. Gino Fallone, for his guidance, and for the concern that he has shown for the future of each of his students. His advice and encouragement brought me through times of difficulty and uncertainty. It has taken me some time to realize the extent of his sacrifice and the difficulty inherent to the task of over-seeing the development of a medical physicist, but he can be assured that his work is appreciated.

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I also thank my colleagues, Mr. Alex Markovic, who helped to develop the analytic, time-dependent, empirical representation of radiation induced conductivity, and Mr. Lawrence Ryner, who measured energy dependence for the radiation-charged electret ionization chamber. I am indebted to Messrs. Michel Morin and Lajos Palotay for their assistance in the design and fabrication of various components of the experimental apparatus, and to Mr. Joe Larkin for his assistance in the design of the electronic components needed in this thesis.

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This thesis is dedicated to my family.
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Chapter 1

Introduction

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1.1 Description of the Electret

In the same way that a magnet is an object exhibiting a quasi-permanent magnetic field, an electret is a sample of material which carries a quasi-permanent electric field. However, whereas the nature of the magnet is dipolar, the electret can possess any combination of monopolar or dipolar charges distributed in any fashion throughout the bulk or surface of the electret. An electret can be formed from a sample of material when an ordered alignment of electrical dipoles is frozen into the material or when charges are deposited onto or into it.

Any sample of insulating or semi-conducting material can be transformed into an electret if it can provide energetically favorable locations or orientations for the trapping of single charges or dipoles, respectively. Waxes, plastics and various inorganic materials such as silicone dioxide (SiO₂) and aluminum oxide (Al₂O₃) have all been used as electret materials through various charging (formation) means and at various times throughout history.

Though the practical applications of the electret stem from the permanence of its electrostatic field, the use is always limited by the eventual decay of the charge or polarization. For the successful use of the electret therefore, the period of application must be short compared to the duration of the charge.

1.2 Electrets in Radiation Dosimetry

The only application of electrets investigated in this thesis is their use in personnel radiation dosimetry: the measurement of energy imparted to the human body by ionizing radiation. As radiation traverses matter, it interacts with particles it encounters and there is a transfer of some or all of the energy from the primary radiation particle to charged particles in the body of the matter, resulting in a distribution of liberated ions throughout the target material. If these ions are collected and counted, and the energy that is required to liberate each ion is known,
the kerma or Kinetic-Energy-Released-in-Matter can be determined by dividing the energy imparted by the mass of the irradiated material. Kerma is closely related to dose, the difference being that, for a given irradiated mass, kerma is the energy density given up by the radiation field, while dose is the energy density absorbed by the matter. Dose and air-kerma are expressed in units of Gray (Gy), where 1 Gy = 1 J/kg. When energy is imparted to matter by a photon, it is usually transferred to an electron, which is then set in motion. As the electron traverses the bulk of the matter, it can ionize atoms or be so roughly accelerated that it emits a photon due to bremsstrahlung, and this photon can carry a portion of the energy with it, away from the mass. Thus the energy that was transferred under the label of kerma can become redistributed in the mass as dose via electronic motion or leave it altogether, carried away by a bremsstrahlung photon.

If electronic-equilibrium is provided for by the presence of a sufficiently thick layer of matter called a build-up region upstream of the point of measurement, the kerma is very nearly equal to the dose. In air, kerma has a value which is extremely close to that of dose because of the low attenuation of the primary photon beam by air. For this reason, our measurements in air will be spoken about in terms of air-kerma, which is a quantity that is theoretically easier to deal with.

Measurement of kerma with electrets is generally accomplished using the principles of operation of the ionization chamber, a device which can be used by itself for the measurement of kerma, but which can also be cumbersome because it requires an external supply of high voltage connected to the chamber by a cable, making it unsuitable for personnel dosimetry. The ionization chamber consists of two electrodes, either flat and parallel as illustrated in Fig. 1.1 (a) or cylindrical and concentric as illustrated in Fig. 1.1 (b), separated by a volume of air and supported by a chamber wall made of a material chosen for its similarity to water or air in the way it attenuates ionizing radiation. Our investigations dealt
Figure 1.1 Typical configuration of (a) a parallel-plate type ionization chamber, and (b) a cylindrical ionization chamber. We used type (a).

specifically with the parallel-plate chamber configuration. When an air molecule between the electrodes is ionized, the liberated ions are drawn by a high electric field to the surface of the corresponding electrode, where there is an exchange of charge between the electrode and the ion. This exchange of charge can be
measured by an integrating ammeter. The electric field in the chamber must be strong enough to prevent the ions from recombining with other ions before they reach the electrodes and must be uniformly perpendicular to the electrodes so that the volume of air from which the ions are collected may be known. The kerma can then be determined since the amount of energy needed to liberate an ion in air is known to be on the average 33.97 eV.

In 1983 a technique was proposed for the formation of thin-film polymer electrets wherein an uncharged polymer film is placed over an electrode in an otherwise normal parallel-plate ionization chamber. The chamber, which we will refer to as a Radiation-Charged Electret Ionization Chamber (REIC), comprises two parallel electrodes separated by a cylindrical air-gap and a thin film of dielectric. When external electrostatic and radiation fields are applied to the REIC, ions liberated in the air-gap drift under the influence of the electric field and become trapped on the surface of the polymer. The charge on the polymer increases by the continual addition of ions until the electrostatic potential at the surface of the electret equals that applied to the opposing electrode, and the electric field between the electrodes is nullified. If the external electric field is then removed, the field which remains, due to the charge trapped on the surface of the electret, is nearly equal and opposite to the previously applied external field. Any ions created in the air-gap at this point will be drawn in the opposite direction so as to reduce the electret charge. In this respect the REIC can serve as a device for the measurement of dose, since, all other things being equal, the amount of charge lost will be proportional to the dose of ionizing radiation received by the air in the chamber.

1.3 Scope and Organization of Thesis

The objectives of the studies described in this thesis were:
1. to obtain a firm understanding of the behaviour of the electric field in the parallel-plate electret ionization chamber as a function of time during charging and discharging and as a function of air-gap;

2. to predict electrostatic charge distributions as charge is deposited and removed from the electret via radiation charging;

3. to describe and demonstrate the effects of radiation induced conductivity on the charging, discharging and use as a radiation dosimeter of the radiation charged electret;

4. to measure the short- and long-term decay behaviour of the radiation-charged, Teflon FEP electret.

In Chapter 2, background material is presented to familiarize the reader with the electret and its applications, with an emphasis placed on its use in personnel radiation dosimetry. Charging methods and measurement techniques are presented. In addition, an analysis of the electret is given, both in terms of electrostatic fields and the currents flowing across the chamber.

In Chapter 3, the materials and methods used in the experimental parts of the thesis are presented, first in general terms which describe those items common to all experiments: the X-ray source, measurement probe, scanning X-Y platform, etc; then in detail, describing the various experimental procedures and the materials specific to them.

In Chapter 4, the measurement of electrostatic charge distributions is described in detail and the results are presented. The distribution of charge was measured at various points during the charging and discharging of the electret. A numerical model that calculates the electric field which governs the charging and discharging of the electret is presented, and the results of the model are used in conjunction with estimations of ion density distributions to predict the deposition of electric
charge on the electret surface. At the end of the chapter, calculated examples of the evolution of the electric field are shown.

In Chapter 5, measurements of radiation induced conductivity (RIC) are presented. The effects of RIC on the charging/discharging curves of the REIC are fitted to a time-dependent analytical equation and incorporated into a set of rate equations describing these curves. The resulting curves are compared to measured ones. The effects of RIC on radiation dosimetry are discussed, and some experiments in which these effects are tested are presented.

In Chapter 6, the charge decay characteristics of radiation charged electrets are discussed, and measurements of both long and short term decay are presented. The decay of electrostatic charge from the surface of charged Teflon FEP electrets was monitored over 195 days, and it is shown that the decay closely follows a model proposed earlier by von Seggern\textsuperscript{5}, with adjustments in the parameters that are thought to be appropriate for the experimental conditions. The results of heat-treatment trials which extend the useful life of the radiation charged electret dramatically are also shown.

In Chapter 7, the dosimetric characteristics of the REIC using the radiation-charged electret are discussed. Here, the sensitivity and reproducibility of the dosimeter are examined.

A list of references, sorted by order of appearance, appears at the end of each chapter, followed by an indexed bibliography at the end of the thesis.

We have presented several aspects of this work at national or international medical physics meetings\textsuperscript{6-17}, published as abstracts\textsuperscript{18-26}, in conference proceedings\textsuperscript{27, 28}, or in various peer-reviewed journals\textsuperscript{4, 29-34}.
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Chapter 2

Background

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2.1 An Historical Perspective

The ability of various dielectrics to retain electrostatic charge has been recognized by man for hundreds, if not thousands, of years. Ancient Greek philosophers are reported to have written about the attractive characteristics of rubbed amber. Beginning with William Gilbert\(^1\) around the year 1600, insulating materials bearing electric charges were given the label, "electrica, quae attrahunt eadem ratione ut electrum" or "electrics which attract in the same way as amber" and were the subject of a great deal of investigation. It was discovered that rosins, pitches, waxes and sulfur could be charged by melting and cooling. In the eighteenth century, preservation of the electret charge was accomplished by surrounding the electret with conductive surfaces\(^2\). The term "electret" was coined in 1885 by Oliver Heaviside\(^3\), though it was applied strictly to dielectrics bearing a dipolar polarization. Electret research was carried on in the early twentieth century by Mototaro Eguchi\(^2\).

Today, the term "electret" has had its definition broadened to include all materials bearing a quasi-permanent electric charge, including piezo-electric materials\(^4\), and there is still a great deal of research carried on to answer fundamental questions about the way in which charge is held and lost by electrets. There is also considerable effort being expended to find new electret materials, charging methods and applications. While the electret of the early twentieth century was typically a thick slab of wax, the modern electret is frequently a thin film of polymer such as Teflon polyfluoroethylene (FEP), Teflon polytetrafluoroethylene (PTFE), or Mylar polyethylene terephthalate (PET), coated on one or both sides by a thin layer of metal.

The electret dosimeter was patented in 1954 by R. Marvin, but insufficient sensitivity to radiation doomed the invention to obscurity.\(^5\) Today, due to advances
in materials science and electronics, the electret dosimeter promises to compete with the most sensitive and reproduceable dosimeters in the world.

2.2 Methods of Formation

2.2.1 Corona Charging

Corona charging is a simple and inexpensive way to obtain uniform charge distributions, ideally suited for mass production of electrets, making it one of the most common techniques for making air-filters, speakers and microphones. A dielectric is corona charged by backing one side of it with a grounded conductor and placing a high-voltage, sharply pointed conductor near the other surface. A highly inhomogeneous electric field exists near the pointed conductor, creating an extremely high electric field strength, which causes the air to suffer dielectric breakdown and allow the free passage of charge carriers from the charger to the surface of the dielectric, where they become trapped. A wire mesh can be placed between the pointed charge source and the dielectric in order to homogenize the field directly above the dielectric\textsuperscript{6, 7}, as shown in Fig. 2.1. The mesh is biased at several hundred volts, while the needle is kept at a few kilovolts.

The charge carriers are primarily \(\text{CO}_3^-\) when charging is done in air at atmospheric pressure\textsuperscript{8} and at a negative bias. Due to their extremely low energy, the ions become trapped on the surface of the dielectric, penetrating very little into the dielectric. Once at the surface of the electret, the ions transfer their charge to local traps and reenter the air.

If charging is performed at a positive bias, the resulting charge layer sits more deeply in the Teflon (FEP) because of the greater mobility of positive charge carriers.

A drawback of corona charging is that the energy levels of the traps have been shown to be reduced under certain conditions, causing reduced charge retention.\textsuperscript{9}
Figure 2.1 Schematic of corona charging, showing the charging needle, a cut-away view of the control mesh, and the dielectric being charged. The electric field, depicted by broken lines, is strongest at the charging needle and draws charge to the dielectric surface.
2.2.2 Liquid Charging

Liquid charging is another simple and inexpensive way of obtaining a uniform distribution\textsuperscript{10} of electrostatic charge. A small amount of liquid, such as water or ethyl alcohol, is used to provide close contact between an electrode and the free surface of a dielectric film, which is backed by another electrode. With the application of an electrostatic potential between the two electrodes, charge double-layers form at both metal-liquid interfaces. At the dielectric surface a charge transfer takes place, and to ensure retention of the charge, either the charging electrode must be withdrawn or the liquid evaporated before the external voltage is removed. Large areas can be charged by moving the electrode over the surface, and high resolution charge patterns can be recorded if the interface between the liquid and the electret is non-wetting\textsuperscript{11}, allowing the liquid drops to form beads.

2.2.3 Tribo-electric Charging

Tribo-electric charging can occur by one of two possible mechanisms: contact or kinetic electrification\textsuperscript{12}, both involving the contact between two solid surfaces. Kinetic electrification is brought about by the rubbing of one solid against another, and is due to an asymmetry in motion that makes the stationary solid hotter than the moving solid. Contact electrification results from a metal-insulator contact and is related to the difference in work-functions between the two materials.

2.2.4 Partially Penetrating Electron Beams

The technique for injecting monoenergetic beams of charged particles into dielectric has been improving for the last fifty years, and is now controllable and versatile. Electrons are used as opposed to ions because of the reduced energy requirement for the same depth of deposition, resulting in less damage to the dielectric.
For practical deposition, the range of the electron beam must be less than the thickness of the dielectric. This requires that for electrets thinner than about 0.1 cm, the charging must take place in vacuum, as electron beams with energies that are low enough to penetrate the film only partially interact excessively with the air they traverse.

When the primary electrons strike the surface of the dielectric, they give rise to the emission of secondary electrons, with a yield in most polymers of 2 to 5 secondary electrons per primary electron at primary energies of 150 to 300 eV, decreasing inversely with energy so that at a primary energy of 10 keV a yield of less than 0.2 is expected. The energy of the electrons drops rapidly as it penetrates the dielectric, so the secondaries generated at depth are quickly stopped in the material. The resulting charge distribution is a positive surface charge and a negative charge layer at the average range or about 2/3 of the practical range. For Teflon, this arrangement can be stable for periods of ten years or more at room temperature.

Scanning beams are usually used to generate a uniform charge distribution, with scanning electron-beam microscopes having been used for this purpose. With electron beams, the charge depth, density and distribution can all be controlled.

### 2.2.5 Fully Penetrating Radiation

Penetrating radiation can be used to displace intrinsic charge carriers rather than to deposit charge in the material. The electrets produced in this way are generally less stable than those formed via the preceding techniques. Either photons or electrons can be used to liberate charge carriers, which can be made to drift by the application of an electric field, or which can be scattered by the Compton effect. In the former case, the separated charge carriers become trapped causing a dipolar distribution. In the latter case, there is a directional preference to the
scattering of the electrons, causing charging even in the absence of an externally applied electric field.

2.2.6 Thermal Charging

Thermal charging is brought about by the simultaneous application of heat and electric field to a dielectric material, followed by cooling of the material while it is still subjected to the electric field. During this procedure, dipoles, either permanent or induced by polarization, are free to orient themselves along the applied electric field when the temperature is high, and become frozen in this position as the temperature is lowered.

For waxes, the temperature has to be brought to a point near the melting point to achieve electrification, while for polymers, the temperature can be less than the melting point so long as it lies above the glass transition point, or the temperature at which the polymer begins to lose all order if the temperature is rising.

The time dependent value of polarization $P_p$ for a polymer held at a temperature $T$ above the glass transition temperature is stated as

$$P_p(t) = \varepsilon_o(\varepsilon_p - \varepsilon_\infty)E\alpha_t\exp(-U_d/kT),$$  \hspace{1cm} (2.1)

where $\varepsilon_o$ is the permittivity of free space, $\varepsilon_p$ is the static dielectric constant of the polymer, $\varepsilon_\infty$ is the optical dielectric constant, $E$ is the electric field strength, $\alpha$ is the dipole relaxation frequency, which is assumed to be singular, $t$ is time, $k$ is Boltzmann's constant, $T$ is the temperature, and $U_d$ is a dipolar activation energy. The rate of increase of polarization is more dependent on temperature than on the strength of the electric field causing it.

In most cases of thermal-charging, the electret-electrode interface can be considered blocking, and the injection of charge from the electrode into the electret absent. This is the case for polymer electrets backed by aluminum electrodes\textsuperscript{14}, the configuration employed in the studies described in this thesis.
2.3 Applications

2.3.1 General

Some practical applications of electrets include: transducers in speakers and microphones; electrophotographic, Xerographic and Xeroradiographic image production; electret motors, gas filters, relay switches and radiation dosimeters.

An electret speaker is a simple device that uses a stretched electret membrane placed near a conductive plate that receives a signal from an amplifier. The alternating attraction and repulsion between the electret and conductor set up vibrations in the electret that emanate sound. The inverse of the same principle can be used to drive a microphone, producing a current from the motion of the electret.

Electret filters\textsuperscript{15, 16} are usually made of long, flat fibers that have been charged so that either opposite surfaces bear opposite charges or each surface bears alternating positive and negative charges. The fibers filter mechanically and electrostatically by attracting charged particles and uncharged particles through induction.

2.3.2 Electret Dosimetry

The permanent nature of the charge in or on an electret makes it ideally suited for personnel dosimetry. If the electret is protected from other external influences, i.e. contact with liquid or solid surfaces, the loss of charge can be attributed to a received quantity of air-kerma. The methodology for the measurement of air-kerma is common to all electret dosimeters. A charge of known magnitude $q_i$ resides on the electret surface before the dosimeter is used to measure a quantity of air-kerma. The charge remaining after a time in the radiation field is measured as $q_f$. The charge lost due to radiation $\Delta q$ is then expressed as:

$$\Delta q = q_i - q_f + q_d$$  \hspace{1cm} (2.2)
where \( q_d \) is the charge lost due to natural electret decay. Because of the high temperature (200 °C\(^1\)) necessary to empty Teflon (FEP) of its most deeply trapped charges, it is generally possible to reduce \( q_d \) to zero by the proper application of heat-treatment prior to the use of the electret as a dosimeter\(^9\). The charge that then remains decays with a characteristic lifetime of roughly 200 years at room temperature\(^1\). The charge lost due to irradiation can then be related to the air-kerma received, though, as we will show, with some dependence on the rate at which the air-kerma was received. We will also show that this rate dependence can usually be reduced to an acceptable level for personnel dosimetry.

As mentioned above, the first electret dosimeter was proposed by Marvin\(^5\), and was based on a thermally charged carnauba wax electret with no polarizing electrode or backing electrode to help define a sensitive volume. This prototype was plagued by low sensitivity and unstable charges. Fabel and Henisch\(^19\) suggested the use of polymer electrets for dosimetry, giving excellent charge retention properties. Subsequent proposals for improved electret dosimeters were given by Perlman and Unger\(^20\), Bauser and Ronge\(^21\), Pretzsch et al\(^22-24\) and others. These more recent electret dosimeters are all based on a modification of either the parallel-plate or cylindrical ionization chamber, with a polymer electret covering one or more electrodes. Various charging techniques have been used in electret dosimetry, but the most popular remains corona charging. The studies performed in the preparation of this thesis were intended to help us understand the physical properties of radiation charged Teflon (FEP) electrets and how these properties affect the use of radiation charged electrets in radiation dosimetry.

### 2.4 Circuit Analysis

#### 2.4.1 Electric fields

The electric field in the dielectric and air-gap can be evaluated theoretically\(^25\)
by the application of Gauss's and Kirchoff's Laws around the circuit depicted in Fig. 2.2. Here, for the sake of generality, the dielectric, with a dielectric strength of $\varepsilon_p$ and thickness $p$, is assumed to be at an arbitrary position between the two electrodes, with air-gaps of width $a_1$ and $a_2$ between the dielectric surfaces and the electrodes; and the charge layer, indicated by the symbol $\sigma$, is situated at an arbitrary depth, $p-r$ in the dielectric, dividing it into regions $a$ and $b$. For analytic simplicity, the edge effects that would be felt by the dielectric are ignored and the charge layer is assumed to have a uniform density.

The electric field strength must now be found for four regions of interest: in the air-gaps above and below the electret, and in the regions above and below the charge layer in the electret. These fields are labeled $E_1$, $E_2$, $E_i$ and $E_{ii}$ respectively.
Gauss's Law applied at the three interfaces of interest: the two dielectric surfaces and the charge layer; and Kirchoff's 2nd Law applied around the circuit, yield these expressions:

\[ E_1 - \varepsilon_p E_i = 0 \]
\[ \varepsilon_p E_i - \varepsilon_p E_{ii} = \sigma/\varepsilon_o \]  \hspace{1cm} (2.3)
\[ -E_2 + \varepsilon_p E_{ii} = 0 \]

and

\[ V_o + a_2 E_2 + r E_{ii} + (p - r) E_i + a_1 E_1 = 0. \]  \hspace{1cm} (2.4)

After appropriate manipulation of Eqs. (2.3) and (2.4), it can be stated that

\[ E_1 = \frac{-V_o + \sigma (r/\varepsilon_p + a_2)/\varepsilon_o}{a_1 + p/\varepsilon_p + a_2} \]  \hspace{1cm} (2.5)

In the set-up used for the experiments described in this thesis, the air-gap \( a_2 \) goes to zero and \( r = p \), allowing Eq. (2.5) to be stated as

\[ E_1 = \frac{-V_o + \sigma p/\varepsilon_p \varepsilon_o}{p/\varepsilon_p + a_1} \]  \hspace{1cm} (2.6)

This is the strength of the electric field in the air-gap of the chamber, and will be referred to as \( E_a \) from this point forward in the thesis. If the external potential is removed, and the upper, polarizing electrode is taken to infinity (\( a_1 = \infty \)), then the potential of the electret surface can be expressed as

\[ V_p = \lim_{a \to \infty} a E_a = \sigma p/\varepsilon_p \varepsilon_o. \]  \hspace{1cm} (2.7)

The highest observed charge density on Teflon (FEP) surfaces has been \( 1.2 \times 10^{-6} \) C cm\(^{-2} \). If this value is substituted into Eq. (2.7), for a 25 \( \mu \)m film, a potential of 16 kV is predicted at the surface of the film.

### 2.4.2 Currents

The current \( i \) in the circuit can be treated in a similar fashion. At any point in the chamber space, the current density \( j \) can be expressed\(^{26} \) as

\[ j(t) = \varepsilon_p \varepsilon_o \frac{\partial E(z, t)}{\partial t} + \frac{\partial P_p(z, t)}{\partial t} + g(z) E(z, t) \]  \hspace{1cm} (2.8)
where $z$ is the position along the chamber axis, $t$ is time, $P_p$ is the quasi-permanent polarization due to ordered dipoles should any exist, $g$ is the conductivity of the medium, and $E$ is the electric field, assumed to be one-dimensional and therefore a scalar quantity. The first term of Eq. (2.8) represents the displacement current, the second represents the depolarization current and the third is the conduction current. The electrets discussed here possess no polarization charge, so the second term always goes to zero.

The currents in the air-gap and in the electret itself must be equal so we can say

$$j = \varepsilon_a \varepsilon_0 \frac{\partial E_a}{\partial t} + g_a E_a,$$  \hspace{1cm} (2.9)

or

$$j = \varepsilon_p \varepsilon_0 \frac{\partial E_p}{\partial t} + g_p E_p,$$  \hspace{1cm} (2.10)

where the subscripts $a$ and $p$ indicate that the quantities are to be evaluated in air or polymer, respectively. These relationships will be very useful when we discuss the effects of radiation induced conductivity in Chapter 5.

### 2.5 Radiation Charging and Discharging

To charge an electret by the method radiation charging, one must assemble a radiation-charged electret ionization chamber (REIC), by placing a thin film of Teflon (FEP) or other suitable dielectric over the collector and guard-ring electrodes of an otherwise normal parallel-plate ionization chamber, a schematic of which is shown in Fig. 3.1. An electrostatic potential must be applied between the guard/collector electrodes and the polarizer electrode, and the sensitive volume of air in the chamber must be exposed to ionizing radiation, which usually entails exposing the entire chamber. Given these conditions, the ions of the appropriate sign, created in the air by radiation, will travel under the influence of the externally applied electric-field and become trapped on the surface of the dielectric, charging
the electret. The ions of opposite sign will travel to the polarizing electrode and a
transfer of charge will occur, allowing current to flow to the electrode backing the
electret, where it contributes to a compensation charge of equal magnitude to the
charge trapped on the surface of the electret. The number of charges trapped on
the electret surface will be a linear function of dose or a quantity called air-kerma
which was defined in Chapter 1, until the electric-field created by the trapped
charge nearly equals the applied field which it opposes. At this time the charging
rate will rapidly fall and the electret is said to be fully charged. To discharge
the electret, one must remove the externally applied electric field and provide a
conduit between the electrodes by short-circuiting them. After this point the ions
created in the air-gap will migrate in such a way that the charge trapped on the
electret surface will be neutralized. It is this effect which permits the REIC to act
as an integrating personnel dosimeter.

The steps followed in the radiation charging and discharging of an electret are
illustrated in Fig. 2.3 which shows the operation of the REIC in both charging
and discharging modes, with both current (a) and integrated current (b) plotted
against time of irradiation. An external voltage of – 400 V was applied across
the air gap for charging, which was performed from 20 to approximately 110
seconds after the beginning of data acquisition. At 110 seconds the electrodes
were short-circuited, and the electret discharged until the end of the acquired set.
The electret became fully charged approximately 50 seconds after the onset of
charging, after which the current flow fell dramatically. From this time until the
beginning of the discharge period however, a small residual current flowed, due to a
combination of leakage in the cables and conductivity of the electret. This residual
current can be seen in part (b) of Fig 2.3 as a slowly changing integrated current.
The electret was completely discharged at approximately the 150 second point,
when the magnitude of the current fell to zero and the integrated current became
constant at a value slightly above zero, due to the residual current which flowed after the full charging of the electret. We can evaluate the practical operation of the dosimeter without concerning ourselves overly with the differences in the integrated current observed between the charging and discharging mode. Some of our work is however, directed toward reducing and better accounting for these differences.

In ideal operation of the REIC, the flow of real charges is limited to the sensitive volume of the air-gap, which remains constant, and the chamber collects ions with one-hundred percent efficiency until the electret is fully charged or discharged at which time the current is reduced to zero. This would result in a charging current-vs-time curve that resembled a step-function, and a discharge curve that was its reflection about the time axis. In reality, the electret is conductive and its conductivity is increased orders of magnitude by ionizing radiation, the sensitive volume changes size because of the edge effects that cannot in practice be entirely shielded by the guard-ring, and the collection efficiency is a continuous function of the electric field between the electret and the electrode opposing it across the air-gap. It was interest in these effects that motivated our work in modelling the electric field during operation of the REIC, and studying the effects of radiation induced conductivity of the electret.
Figure 2.3 X-ray exposure, applied potential, current and integrated current shown as functions of time for both charging and discharging. Data points gathered every 0.365 s. For this set of data, an air gap $a$ of 4 mm was used with a collector radius $r$ of 5 mm and a guard ring width $r_g$ of 20 mm.
References


# Chapter 3
## Materials and Methods

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3.1 General

A general description of the materials and apparatus common to all of the experiments is given in this section, which is followed by a detailed description of each experimental procedure. The materials that were used in the formation of electrets in these studies were films of Teflon (FEP) (I.E. DuPont de Nemours & Co.), or Mylar PET of varying thicknesses. The construction, in cross-section, of the cylindrical chambers housing the electret was as shown in Fig. 3.1 with various materials used to make the walls and electrodes of various dimensions.

When either the current or charge flow was to be measured, a Keithley 35627 electrometer or Keithley 428 current amplifier (Keithley Instruments, Inc., Cleveland, Ohio) were used, each of which is capable of measuring down to $10^{-15}$ A. A Keithley 245 high voltage supply was used to provide the external

![Figure 3.1 Schematic of ionization chamber used to produce the electret.](image-url)
potential, up to 1999 V, for charging, and the most commonly used source of ionizing radiation was a Hewlett-Packard Faxitron X-ray system (Hewlett-Packard, McMinnville Division, McMinnville, Oregon), capable of continuous output of a 30 – 110 kVp beam at a tube current of 0 – 4 mA.

Data was sampled at a rate of 3.125 s⁻¹ from the electrometer, or at a variable rate reaching values as high as 500 s⁻¹ from the current amplifier. The data was then collected by a personal computer on which analysis was carried out using commercial and in-house software.

Measurement of surface potential was done by dismantling the REIC, and placing the wall bearing the electret and its backing electrode on a specially built frame which was rigidly attached to a motorized X-Y platform that is capable of finely controlled motion in the plane of the electret. Measurement was typically performed by scanning the electret surface, placed 2 mm beneath the probe, in a two-dimensional raster fashion, while the probe remained fixed in the laboratory frame of reference.

3.1.1 The Radiation-Charged Electret Ionization Chamber

The chambers which house the electrets were made of two circular, polystyrene end walls with a Lucite ring used to separate them. The Lucite rings were 0.4 cm thick and of various heights a. A concentric circular channel, 0.4 cm wide and 0.1 cm deep was cut into the inside surface of both end walls to provide a snug fit for the spacer ring when the chamber was assembled. The chambers were assembled by snapping the parts into place. A more secure fit was not needed since these chambers were intended only to be studied, not to be worn as dosimeters. A similar channel was cut into the outside surface of the walls to allow placement of the wall on the frame attached to the X-Y platform. For measurement of the electret surface charge, it was desired to place a grounded, conducting surface around the electret, so a channel 1 cm wide was cut from the inside surface of
the wall supporting the electret. Before scanning, a 0.1 cm thick copper ring was placed in this channel, providing a grounded surface for reference. The aluminum strip contacting the collecting electrode lay beneath the copper ring so that the collecting electrode would also be at ground potential.

The Teflon (FEP) was purchased (Sheldahl Plastics, Inc. Northfield, MN) in sheets of various thicknesses with thin (on the order of several nanometers) coats of aluminum deposited on one side by condensation. The samples were cut from these sheets and affixed with a water soluble glue to the polystyrene end wall, on which had previously been secured the aluminum contact. The contacts were secured with two-sided tape to the polystyrene surface. The details of the chamber construction are shown in Fig. 3.2, though not to scale.

3.1.2 X-ray source

The Hewlett Packard Faxitron X-ray cabinet, model number 43855A, produces the X-rays used in the charging and discharging of the electrets studied here. It houses a self-rectified X-ray tube and is capable of continuous operation over very long exposure times. The tube current and peak potential can be controlled independently by the operator, albeit with poor precision: ± 0.17 mA and ± 0.5 kVp, respectively. A maximum tube potential of 110 kVp and a maximum tube current of 4 mA can be maintained over periods on the order of hours. Some drift of tube current occurs as the tube heats, and must be compensated for by the operator. The beam was operated at an output of 2.3 mJ kg⁻¹s⁻¹.

The beam profile at the standard source-to-chamber distance of 53 cm was measured using film and a digitizing densitometer. Kodak XV film was exposed at 93 kVp for 0.33 min. and the resulting optical density was recorded with a CCD video camera, then entered into computer memory. The profile of relative dose derived from this information is shown in Fig. 3.3. The duration of irradiation was
Figure 3.2 Cut-away exploded view of chamber construction. Not to scale.
chosen so that the film would be in the linear, and most sensitive portion of its response curve. The beam is seen to be quite uniform across the central circular area of 10 cm diameter, with a variation of not more than 0.3 %. Placement of the electret during charging or discharging was reproducible to within 1 cm during the experiments.

3.1.3 Platform

The X-Y platform (Aerotech, Inc., Pittsburgh, PA) is a servo-motor operated unit, controlled by a two-axis microprocessor-based motion controller (Model
Platform velocities and acceleration times can be set from 0 to 101.6 cm/s and upward of 10 ms, respectively, with distance specifiable to 2 μm. The controller can be programmed from its front panel, externally via an IEEE488 Interface Bus, or operated interactively via the same bus. Most of the instructions given to the controller were issued by one of several Pascal programs we wrote expressly for these studies, and run on a personal computer.

When scanning the electret, the data points returned from the electrostatic probe are assumed to be acquired at evenly spaced intervals — a valid assumption when the platform moves with constant velocity. To eliminate the effect of acceleration time on point placement, the platform was programmed to begin each scan such that the edge of the electret would be sufficiently far from the probe that the platform’s programmed velocity could be achieved before measurement of the electret had begun. Thus the first few data points from each pass of the platform were discarded. It was important also that the inter-point spacing be independent of the two principal axes: to achieve this, the timing of data acquisition was carefully adjusted so that one data point would be taken per mm of scan distance, which was equal to the inter-scan spacing. It was established that the data acquisition program requires 0.028 s/sample, requiring a speed of 3.6 cm/s to give 1.01 mm/sample.

3.1.4 ADC

An analog-to-digital converter (ADC), model ADC488/8s (IOtech Inc., Cleveland, OH), was used to convert the analog signals from the electrostatic voltmeter to a 16 bit digital format for acquisition by the personal computer. The ADC is capable of 100,000 conversions per second when one input channel is sampled, and can be controlled via the IEEE488 bus from an external processor. The program that controls the platform is also responsible for data acquisition, setting the sampling rate, and triggering the acquisition of data for transmission to computer memory.
3.1.5 Electrostatic Probe

The electrostatic voltmeter (ESVM) model 344 (Trek, Inc., Medina, NY) uses a vibrating capacitor to measure the local electrostatic potential of a surface placed beneath it — a technique commonly used in the measurement of electret charge. An amplified signal that is independent of probe-to-surface distance (PSD), is then input to an ADC. The capacitor is housed in a probe that is connected to the ESVM. The "window" through which the capacitor senses the surface beneath it is $0.78 \pm 0.005$ mm in diameter.

The capacitor is attached to the face of a piezoelectric crystal which uses an AC signal applied at a frequency of approximately 700 Hz to drive its oscillatory motion. When placed in an external electric field, the vibrating capacitor sends an AC signal, the amplitude of which depends on the strength of the electric field, to the ESVM which attempts to minimize the signal by applying an electrostatic potential to the capacitor. When the potential of the capacitor equals that of the measured surface, the capacitor no longer feels an electric field and the DC voltage of the capacitor stabilizes. The process requires a maximum of 2 ms to measure a surface at 2000 V.

Ideal operation requires the PSD to be as small as possible to minimize the signal noise, which rises with distance according to the curve shown in Fig. 3.4. This information was obtained by positioning the probe over a conducting surface held at 200 V and acquiring 100 samples per data point. The PSD used in the measurements described in this thesis was 2 mm, giving rise to a measurement error of $\pm 0.5$ V, independent of the voltage of the measured surface. The spatial resolution of the measurement system is also adversely affected by the PSD as is shown in Fig. 3.5. These curves were obtained by scanning with varying PSDs a 0.1 mm wire held at 200 V above a grounded conducting plate. The minimum, practically attainable PSD was 0.3 mm, for which a curve with a full
Figure 3.4 Standard deviation of 100 readings of surface potential for various PSDs measured over a surface held at 200 V.

width of 0.8 mm at half the maximum peak was obtained. Beyond the dependences mentioned above, the mean measured value of surface potential shows a negligible linear dependence on PSD over the small range of possible positioning error, which was less than 1 mm in extent.

Before the scanning of an electret, the probe was zeroed by measuring the potential of a surface sharing the same ground as the electrode backing the
Figure 3.5 A series of measurements of a 0.1 mm wire charged to 200 V, for three PSDs.

electret. The value returned from this measurement was then subtracted from each measurement of the electret surface.

The probe was calibrated by measuring a known surface, i.e. a conductor held at a given voltage, and adjusting the gain until the proper reading was obtained. Once calibrated, the probe provided very stable output, showing no measurable drift in a period of three years.

3.1.6 Properties of Teflon

The chemical definition and structure of two types of Teflon and Mylar are
shown in Table 3.1. Teflon is a common choice for electrets regardless of the choice of charging technique. Teflon is chosen because of its capacity for long charge storage periods. It has a low intrinsic conductivity at room temperature \( \approx 10^{-22} \, \Omega^{-1} \text{cm}^{-1} \) and is very hydrophobic. These properties cause low charge leakage through the bulk of the electret and through the air, respectively.

Other properties of Teflon (FEP) are\(^2\): a density of 2.2 g/cm\(^3\), a dielectric constant of 2.11, and a dielectric strength, which depends on thickness, of 1000 kV/cm at a thickness of 2.5 \( \times 10^{-3} \) cm and 13 kV/cm at a thickness of 0.25 cm.

### 3.2 Measurement of charge distribution

For the measurement of charge distributions, the REIC was composed of polystyrene end walls (4 mm thick, 45 mm radius) and Lucite spacer rings (4 mm thick, the inner surface having a 35 mm radius) of various heights \( a \) (2 or 8 mm). The polarizing electrode was a circular area (25 mm radius) painted with
carbon (Aquadag, Acheson, Canada) while the dielectric material was 0.254 mm thick Teflon (FEP) bearing a thin (~1 μm) layer of aluminum which served as the collecting electrode (also of 25 mm radius).

The electrets were scanned in a raster fashion beneath the electrostatic probe at various points during the charging and discharging of the electret in the REIC. To accomplish this, the irradiation of the chamber was interrupted, the chamber disassembled and the wall bearing the electret placed on the scanning frame. Each scan produced 64 lines of data 73 ± 1 data points long. The data were processed by removing the first and last four points from each scan line to eliminate any distortions due to acceleration or deceleration, then, if the number of data points were to still exceed 64, removing randomly selected points to bring the number in each scan line to 64. This process is designed to generate a two-dimensional matrix with uniform point spacing in the two directions.

The next step in processing was to pass the data through a program which would calculate, for a given radial coordinate origin, both the average measured value and the standard deviation in annuli 1 mm wide at radii in steps of 1 mm from 0.5 to 24.5 mm. The coordinate origin is initially assumed to be the 32nd point in the 32nd row, as this is how the scanning process was designed to be carried out, but because placement of the electret on the moving frame could vary by up to 1 mm, the processing program shifts the coordinate origin in 0.5 mm increments in a 2 mm square centered on the 32nd point of the 32nd row, and chooses as the true origin that point which produces the smallest average standard deviation for the data averaged around the angular coordinate θ. The result of each scanning procedure is then a charge profile, composed of points representing average surface potential at a given radius.

Charging took place while applying an external potential to the polarizing electrode and irradiating the chamber with a 100 kVp X-ray beam of effective
energy approximately equal to 29 keV generated in a Hewlett-Packard Faxitron cabinet. Whereas in our previous studies\textsuperscript{3, 4}, electrical connections were provided by fine zinc wires, it was found that these wires could lead to the corruption of charge uniformity by acting as intense sources of scattered radiation.

The result of the scattered radiation was a local increase in the concentration of liberated ions, allowing the electret to collect more charge at points closer to the contact between the backing electrode and the wire. Because of this, the circular symmetry of the system was perturbed, and the data, when averaged over the angle $\theta$, showed a slight increase in charge density near the edge of the electret. Electrical connections were therefore provided by thin aluminum strips, with attention paid to limiting the degree to which the connector extended into the volume of the REIC.

It should be mentioned that a change in the electret material from 0.11 mm Mylar\textsuperscript{3} to 0.254 mm Teflon (FEP) had no observable effect on the measured distributions. This change was affected solely because of the more desirable charge retention characteristics of the Teflon (FEP)\textsuperscript{5}, which render it more suitable for use in personnel dosimetry.

In order to determine the spatial resolution of our measurement system, a circular step function was created for measurement by charging a circular aluminum electrode to 100 V and surrounding that with a grounded guard ring. When this configuration was scanned and the data averaged, it was found that by convolving a step function with a Gaussian function of full-width-half-maximum (FWHM) equal to 3.8 mm, we could accurately reproduce the averaged data as is shown in Fig. 3.6. It therefore seems appropriate, when comparing measured and calculated data, to convolve the calculated distributions with this same Gaussian line-spread-function. The error-bars, representing standard deviations of samplings around a given radius, are typical of those obtained in the measurement of electret
Figure 3.6 Results from the measurement of a circular electrode charged to 100 V and from the convolution of a step function with a 3.8 mm FWHM Gaussian. The error bars represent the standard deviation from the averaging of the measured data.

charge distributions, and are probably due to some combination of the error in point-placement due to the assumption of uniform inter-point spacing and the error in cutting a circular film of dielectric.
3.3 Radiation Induced Conductivity

For the determination of the effects of radiation induced conductivity on the dosimeter as a whole, we used, as described in the Introduction, our REIC which resembles a parallel-plate ionization chamber except that the collecting electrode is covered with a Teflon (FEP) film (see Fig. 3.1). One side of the film is aluminized and connected to an ammeter. The other side of the Teflon (FEP) faces the polarizing electrode 0.4 cm away. The polarizing electrode is a film of carbon facing the inside of the REIC, and is connected to a Keithley 245 high-voltage power supply.

For the measurement of radiation induced conductivity alone, Teflon (FEP) samples having a thin electrode on both sides were used. The Teflon (FEP) samples were 2.54 × 10⁻² cm-thick foil disks, 5 cm in diameter, with a 4 cm diameter aluminum layer (∼1 μm thick) on one surface. Samples were prepared with a 1 cm radius collector surrounded by a 1 cm wide guard ring formed by etching the aluminum surface. The collecting electrode was connected to a Keithley 35617 electrometer with an IEEE-488 port to a PC. A graphite polarizing electrode (Aquadag©) was painted on the other surface of the samples and was connected to a Keithley 245 high-voltage power supply. The electrode materials were chosen in an effort to recreate the radiation environment to which the Teflon (FEP) is exposed in the REIC. We found that the steady state RIC with this choice of electrodes is similar to that observed with the REIC at the end of the charging process.

The temporal resolution of all the data acquired varied from 3.125 samples/sec to 100 samples/sec. The X-rays were produced by a Hewlett Packard Faxitron with a tungsten target and beryllium window. Our measurements were performed under irradiation with a peak tube potential of 90 kVp giving an effective energy of 25 keV. The output of the X-ray tube is measured in units of air-kerma,
which is defined as being equal to absorbed dose in air under conditions of electronic equilibrium\(^6\). The readings from the REIC were compared to those from a calibrated ionization chamber and conversion to dose in a material other than air is possible through multiplication by the standard conversion factors\(^5\). The X-rays causing the air-kerma were produced by a Theratronics cobalt-60 unit, having an effective energy of 1.25 MeV and an output of 19 mGy/s at 80 cm with a 5 cm × 5 cm field.

In order to test the expectation that the REIC reading depends on the rate at which air-kerma is delivered\(^7\), an experiment was designed in which the REIC was fully charged and irradiated several times: each time to the same air-kerma, but at different rates. The combinations of air-kerma and rate were chosen so that a measurable difference in surface potential would exist between each case. An air-kerma of 10 mGy, delivered at rates of 0.005 mGy/s, 0.6 mGy/s and 16 mGy/s was chosen. For the experiment, the electret was charged to a surface potential of 1000 V in the standard manner, then heat-treated at 95 °C for 10 minutes, after which the surface potential was constant at about 450 V. Before and after each irradiation, the chamber was disassembled and the central surface potential of the electret was measured by mounting the electret on the X-Y platform and bringing the electret to a fixed position beneath the probe. The average of 100 data-points acquired from the probe was then taken as the potential. The chamber was then reassembled and the collecting electrode shorted to the polarizing electrode.

The radiation output of the \(^{60}\)Co unit was measured on the day of the experiment using the “American Association of Physicists in Medicine” protocol TG-21\(^8\). Through this it was found that the dose rate to a calibrated ionization chamber situated 85 cm from the Co source 5 cm deep in a phantom of tissue-like plastic (Lucite), was 84.4 cGy/min. This was then converted to the dose rate that a small sample of Lucite, centered at a distance of 80 cm would experience through
division by the tissue-air ratio\(^6\) \((\text{TAR}(5 \times 5 \text{ cm}^2, d = 5 \text{ cm}) = 0.847)\) and corrected for distance by multiplying by \((85/80)^2\). We then found the kerma-rate to the air through multiplication by the ratio of mass absorption coefficients for air and Lucite\(^6\), \(\left(\frac{\mu_{\text{air}}}{\rho}\right)_{\text{air}} / \left(\frac{\mu_{\text{Lucite}}}{\rho}\right)_{\text{Lucite}} = 0.942\) evaluated at an energy of 1.25 MeV, giving a value of 17.7 mGy/s.

The REIC was placed 80 cm from the cobalt-60 source as shown in Fig. 3.7, and the radiation was attenuated by 0 cm of Pb or 5 cm of Pb, reducing the air-kerma rate at the REIC to 17.7 mGy/s and 0.6 mGy/s respectively. The REIC was then placed at a distance of 160 cm from the cobalt-60 source with 10 cm of Pb filtering the primary beam, reducing the air-kerma rate at the electret to 0.005 mGy/s. The values expected for the latter two quantities from the application of the laws of exponential decay and/or inverse-squared distance correction would be 0.65 mGy/s and 0.006 mGy/s, using a mass absorption coefficient\(^6\) for lead of 0.00581 m\(^2\)/kg, but the geometry of the set-up used renders the REIC susceptible to scattered radiation from the lead filtration. This was not a problem, as the actual air-kerma rate had been determined experimentally. The time required for each of these irradiations was 0.6 s, 16.7 s and 2000 s.

### 3.4 Charge Decay

For the study of long-term decay, the end walls and spacer ring of the chamber were constructed of Bakelite. We used 25 \(\mu\)m and 75 \(\mu\)m thick samples of Teflon (FEP) and 110 \(\mu\)m thick samples of Mylar (PET), with thin aluminum electrodes deposited on one side. The electret and chamber walls were 48 mm in diameter with a 3 mm air-gap. The backing electrode consisted of a 12 mm thick guard-ring surrounding a 25 mm diameter collector. Irradiation was performed with an X-ray beam of 90 kVp and a HVL of 2 mm aluminium, to an electret surface potential of 200 V.
Two of the electrets were exposed to a temperature of 100°C for 10 minutes before charging, two were cleaned with acetone before charging, and one was deliberately soiled by smudging with finger tips. After charging the electrets, the REICs were placed in a desiccating bowl at a relative humidity of 15% and at room temperature. At various intervals the chambers were removed and disassembled at which time the electret was measured with a Trek electrostatic probe.

For short-term decay studies, the electrets were 254 μm or 25.4 μm thick Teflon (FEP) samples, charged to 200 V in a chamber with a 0.4 cm air-gap. The charging was performed in the Faxitron at a tube potential of 100 kVp and a tube current of 4 mA, requiring 30 seconds to charge the 254 μm electrets and 3 minutes to charge the 25.4 μm. The electret surface potential was measured within seconds of the termination of the charging procedure by scanning a small
area at the centre of the electret over a period of roughly two seconds and averaging the results, and the electret was returned to its chamber housing immediately afterward. At intervals of from 15 to 30 minutes, the electret was remeasured in the same manner. The scanning procedure ensured that the same area on the electret surface would be measured each time, since the electret was rigidly mounted on the scanning frame. This was carried on for periods of three hours. After the final measurement, each electret was discharged completely and recharged. Five electrets were used, four were of the 254 \( \mu \text{m} \) thickness and one was of the thinner 25.4 \( \mu \text{m} \) thickness. Statistics were compiled with reference to particular electrets, trials and thicknesses, in an effort to characterize the short-term behavior of the freshly charged electret.

The effects of heat treatment on the short and long-term decay patterns of the radiation charged electret were investigated. Electrets were charged, then exposed to temperatures of 95 \( ^\circ \text{C} \) for periods of ten minutes or longer. The surface potential of the electrets was then measured on an hourly basis for the first several hours and on a daily basis for the following two weeks. Between measurements, the electret was stored in a bowl at a relative humidity of 20 %.

### 3.5 Dosimeter Characteristics

For the studies dealing with the energy dependence of the REIC, chambers were constructed with 1.5 mm thick fiberglass backing, various collector radii \( c \) (0.5 to 1.9 mm), guard-ring widths \( g \) (1.0 to 19.0 mm) and air-gaps \( a \) (1 to 9 mm). Small pin connectors were added to allow simple connection to the current measurement equipment and removal from the equipment when the dosimeter was to be used for monitoring. Most of the measurements were performed using the Hewlett Packard Faxitron X-ray system. Some measurements were also performed on a highly reproducible diagnostic X-ray unit (Siemens Polydoros 80). Energy dependence
for the chamber was verified for photons with effective energies from 17.5 keV to 1.25 MeV using the Faxitron, a Philips RT250 orthovoltage unit (100 kV<sub>p</sub> with HVL of 0.32 mm Cu, 150 kV<sub>p</sub> with HVL of 0.62 mm Cu, 200 kV<sub>p</sub> with HVL of 1.3 mm Cu, and 250 kV<sub>p</sub> with HVL of 2.3 mm Cu), and a Theratronics 60Co source (Atomic Energy of Canada, Ltd.). The widths of the energy spectra varied from two to three times the effective energies for both the Faxitron and Philips tubes. Calibration measurements were performed with a 15 cm<sup>3</sup> parallel-plate chamber connected to a Keithley 35055 electrometer, and a 0.6 cm<sup>3</sup> Farmer chamber connected to a Nuclear Enterprises 2570 reader.

Current and charge measurements obtained from the REIC were accomplished using a Keithley 35617 electrometer connected in series with and without the external power supply. The electrometer has a response time of 320 ms. Charge decay measurements were done by removing a dosimeter from storage in a desiccating chamber at 20% relative humidity, dismantling it and placing a stationary, non-contact electrostatic probe connected to an electrostatic voltmeter (Trek 6000B and 344) at about 1 mm above the electret opened to air.
References


4.1 Introduction

In order to build a REIC with the largest possible dosimetric range and greatest possible sensitivity, it is important to understand the evolution of the electric field within the REIC during its life-cycle. This is a very difficult quantity to measure, but it can be predicted with the help of Laplace’s and Gauss’s equations. Having arrived at a solution for the electric field, we can then predict its effects in terms of the distribution of charge deposited on the surface of the electret during charging, and this we can compare directly to measured data. This comparison provides an opportunity for judging the quality of the calculation of the electric field.

Previous work by Fallone and Podgorsak\textsuperscript{1} on the dynamics of the radiation charging and discharging process concerned itself with the total charge accumulated and depleted, respectively, within an area defined by the border between a collection electrode and a guard-ring, as measured by an external electrometer. Calculations were approximate since the law of Gauss that was used to describe the electric field in the sensitive chamber volume is rigorously true only at the interface between the polymer and the air, and does not consider the large air-gap or the finite area of the electrodes. Calculations of electric fields by solving Laplace’s equation within REIC’s have been presented\textsuperscript{2-4}, but solutions apply only to limited regions of the chamber. Furthermore, these calculations do not consider the time-dependent change of electric field and thus the changes in surface charge distribution during the radiation-charging and discharging of the electret. Measurements have shown considerable changes in electret surface charge distribution during the process of radiation-charging and discharging due, it is believed, to the particular size and geometry of the chamber.

Measurements of the two-dimensional surface charge distributions on radiation-charged electrets at various points in time during the charging and discharging cycles\textsuperscript{5,6} revealed that the uniformity of charge distribution varies with the size
of the air-gap separating the free electret surface from the polarizing electrode, with greater uniformity observed at smaller air-gaps. This is to be expected since, as the ratio of air-gap to chamber diameter grows smaller, the system approaches an ideal, one-dimensional configuration, in which perfect charge uniformity would exist for reasons of symmetry. The effect of the edges of the system on the electric field and the consequent charge distribution were not intuitively obvious, however, so an attempt was made to numerically predict the electric-field and predict charge deposition patterns in accordance with the modelled field.

The time dependent, radial charge distributions as they were originally measured are shown in Fig. 4.1. These curves were obtained during the charging of the electret in (a) 2 and (b) 8 mm air-gap chambers to a potential of 200 V. A similar set of curves is shown in Fig. 4.2 obtained during the subsequent discharge of the same electrets. The time after the onset of radiation is denoted in minutes at the center of each curve. These measurements were hampered by mechanical difficulties which prevented scanning the electret beyond a radius of 16 mm. The initial conclusion drawn from them was that a concave distribution is generated during the charging of a chamber with a thin air-gap, and a convex distribution is obtained during the charging of a chamber with a large air-gap. Another attribute, seen in Fig. 4.2, is that in discharging the electret, the sides of the distribution are neutralized before the centre, with the separation between the edge of the "center" and beginning of the "side" more defined in the case of a smaller air-gap.

It was also found that the charge distribution could be easily influenced by the materials surrounding the electret. The importance of the choice of materials for construction of the chamber housing the electret, and how that choice affects the measurement of distributions, is best illustrated by showing the non-uniformity of charge deposition that results when a source of scattered radiation is introduced to the chamber. Examples of such two dimensional charge distributions are shown
Figure 4.1 Charge profiles measured as a function of radial position to 15 mm during the charging of electrets at an air-gap of (a) 2 mm, and (b) 8 mm. The time after the onset of radiation is denoted in minutes at the center of each curve.
Figure 4.2 Charge profiles measured as a function of radial position to 15 mm during the discharging of electrets at an air-gap of (a) 2 mm, and (b) 8 mm. The time after the onset of radiation is denoted in minutes at the center of each curve.
in Fig. 4.3, where the horizontal axes represent position and the vertical axis represent the measured surface potential. The effects of scattering materials on the distribution of charge can be seen in parts (a) and (b) which were obtained midway through the charging of a 0.0254 cm thick Teflon (FEP) electret to a potential of 200 V in a chamber with a 0.4 cm air-gap. The configurations corresponding to the distributions of Fig. 4.3 are shown in Fig. 4.4, with the location of a small (2 x 2 x 2 mm$^3$) steel scattering source indicated by the small solid rectangle. For the scatter to have an effect, the scattering source must be opposite the electret. This suggests the possibility that it is the scattered secondary electrons themselves that become trapped on the surface of the electret. It was decided that a minimum of scattering materials should be present during charging and discharging, at least while the charge distributions were being studied.

The configuration shown in Fig. 4.4 (d) has only thin (0.1 mm) aluminum strips (2 – 3 mm wide) to provide contact with the electrodes and these extend beyond the walls of the chamber. When the electret is charged under such conditions, the resulting deposition of charge is very uniform, as is seen in Fig. 4.3 (d). Here the circular symmetry of the set-up remains intact and the data may be averaged over the angular coordinate to produce a radial map of charge distribution.

The distributions shown in Figs. 4.1 and 4.2 were obtained using thin zinc wires to provide the contact to the polarizing electrode. It was found that the scatter produced by these wires, as depicted in the example illustrations of Fig. 4.3, was what lead to the apparent concavity of charge distributions seen in Fig. 4.1. When the zinc wires were replaced with aluminum strips, the charging distributions for chambers having small air-gaps became very uniform.
Figure 4.3 Examples of the way in which scattered radiation can corrupt the uniformity of a charge distribution. (a) charge density spike caused by scatterer on polarizer lead and on exit surface of chamber, (b) smaller spike caused by scatterer on polarizer lead and on entrance surface of chamber, (c) very little non-uniformity with scatterer on electret lead, (d) no scatterer.
In one of our previously published papers, a numerical solution method was used to solve Laplace’s and Gauss’s Equations in and around the REIC and then predict the radial distribution of electric surface-charge as a function of time during the charging and discharging processes. From the results of this calculation, the trajectory and strength of the electric field within the REIC were then evaluated. In the determination of the charge distribution on the surface of the electret, it was assumed that ions generated in the REIC follow the lines of electric-field and that ions are distributed with uniform density throughout the REIC during irradiation. Because of these assumptions, it was necessary only to calculate the area bounded by adjacent electric-field lines to know the charge which was to be deposited on
the electret surface. For the algorithm, which we will call the First Model, to work successfully, it was required that the electric-field lines be well behaved, never doubling back, not diverging excessively and not bending too abruptly.

We have since modified our method of calculating charge distributions through the application of several assumptions regarding the distribution of ions generated by the ionizing radiation field: via the calculation of ion-densities by estimating the trajectories and energies of recoil electrons resulting from the scattering of incident photons, and alternatively by assuming that all scattered recoil electrons are distributed isotropically, their density being inversely proportional to the square of the distance from the scattering point. In addition, we have changed the method by which the collection of charge from within the REIC is calculated, and the way in which the calculated data is presented, i.e., through convolution of the calculated distribution with the line-spread-function of the measurement system. The refined algorithm will be referred to as the Second Model. Finally, we have improved the measurement of surface-charge distributions, allowing us to map the full surface of the electret. In this chapter we will present and discuss both the First and Second models.

4.2 Electric Field Solution Method

Before describing the First and Second models, we will discuss the determination of the electric field in and around the REIC. In this calculation, an iterative technique is used for the piece-wise linear solution of Laplace's equation in two dimensions with cylindrical coordinates

$$\nabla^2 \phi = 0$$  \hspace{1cm} (4.11)

applied at points in bulk, where $\phi$ is the electrostatic potential, and Gauss's Law

$$\varepsilon_1 E_1 + \varepsilon_2 E_2 = \frac{\sigma}{\varepsilon_0}$$  \hspace{1cm} (4.12)
applied at interfaces, where $E_m$ is the normal electric field component in material $m = 1$ or 2, $\varepsilon_m$ is the relative dielectric strength of material $m$, $\varepsilon_0$ is the permittivity of free space, and $\sigma$ is the charge density trapped at the interface. Typically 1000 iterations are performed to ensure sufficient relaxation of the system.

One obstacle to the solution of Eq. (4.11) for the set-up described was the lack of known boundary conditions at the edge of the REIC. This is due to the fact that the wall of the chamber is a nonconducting dielectric. The solution proposed here requires that a grounded conducting wall surround the chamber at a distance which is large compared with the dimensions of the chamber, as is shown schematically in Fig. 4.5. This is a reasonable assumption as our chambers are charged and discharged while in a grounded, metal cabinet. Some spatial resolution is, unfortunately, lost in the calculation of the field strength in the chamber since the calculations must also be performed in the space between the chamber and the wall of the cabinet, requiring more time and computer memory. The distance from the chamber to the cabinet wall is unimportant so long as the change in the solution brought about by a change in this distance is small.

The numerical solution to Eq. (4.11), expressed in axi-symmetric cylindrical coordinates is

$$
\frac{(\phi_1 + \phi_2 + \phi_3 + \phi_4)/4 + \Delta r/8r(\phi_3 - \phi_4)}{\varepsilon_0} = \phi_0
$$

where $r$ is the distance from the centre of the chamber, which coincides with the origin of the coordinate system, $\Delta r$ is the distance between points in the discretized radial direction, and $\phi_i$ is the electrostatic potential at point $i = 0...4$ as shown in Fig. 4.6.

The numerical solution to Gauss's law, applied at the interface between two dielectrics (air/Teflon, air/polystyrene), can be expressed as

$$
\frac{\varepsilon_1 \phi_1 + \varepsilon_2 \phi_2 - \sigma \Delta n/\varepsilon_0}{\varepsilon_1 + \varepsilon_2} = \phi_0
$$

(4.14)
Figure 4.5  Schematic diagram of the space in which the solution to Laplace's and Gauss's equations are sought.
where $\varepsilon_1$ and $\varepsilon_2$ are the dielectric constants of materials 1 and 2, respectively, $\phi_1$ and $\phi_2$ are the potentials at points on sides 1 and 2 of the interface, $\sigma$ is the density of charge trapped on the surface, and $\Delta n$ is the inter-point spacing in the direction normal to the surface of interest. Eqs. (4.13) and (4.14) were evaluated iteratively at every point in the solution space and at every interface point.

4.3 Collection Efficiency

Theoretical treatment of collection efficiency has always dealt with a chamber as a whole, but we required an estimate of collection efficiency on a local basis, i.e., what fraction of charge generated at a specific site in the chamber is collected by the electrodes.
For the purposes of estimating collection efficiency, or the fraction of ions generated in the chamber that are collected on the electret surface and not lost due to recombination, each cell is treated as an individual ion chamber and the difference in potential from one side to the opposite is treated as the applied potential. As reported previously, the collection efficiency for each cell can be expressed as \( f = \left( \frac{\sqrt{b}}{1.410} \Delta \phi + b(\Delta \phi)^2 \right) / \left( 1 + \frac{\sqrt{b}}{1.410} \Delta \phi + b(\Delta \phi)^2 \right) \), (4.15)

where \( \Delta \phi \) is the potential difference across the cell, and the parameter \( b \) is defined as

\[
b = (1.828)^2 \left( \frac{\mu_1 + \mu_2}{\Delta s^2 (\alpha_o/e)^{1/2} (\kappa/\kappa)^{1/2}} \right)^2,
\]

where \( \mu_1 \) and \( \mu_2 \) are the mobilities in air of the positive and negative charge carriers, respectively, \( \Delta s \) is the length of the axial edge of the cell, \( e \) is the electronic charge, \( \alpha_o \) is the recombination coefficient, and \( \kappa \) is a factor for converting air-kerma rate to current. For \( \mu_1, \mu_2, \) and \( \alpha_o \) we use the published values of \( 1.30 \times 10^{-4} \) m\(^2\)/Vs, \( 1.80 \times 10^{-4} \) m\(^2\)/Vs, and \( 1.95 \times 10^{-12} \) m\(^3\)/s. For the value of \( \kappa \) we use 0.381 C m\(^3\)Gy\(^{-1}\) which is the ratio of the density of air at standard temperature and pressure (0 °C and 101.3 kPa, respectively) and the average energy needed to create an ion-pair in air.

We originally felt that collection efficiencies should combine multiplicatively as charge advances through the REIC. Figure 4.7 shows the result of a typical series of charging calculations for a chamber with an 8 mm air-gap being charged to 200 V, and for which it was assumed that collection efficiencies combine multiplicatively. The important characteristic of this set of curves is the way in which the intercurve spacing diminishes rapidly as charging proceeds despite the fact that the curves are obtained at uniform time intervals, and the surface...
potential is far from the applied potential when the charging begins to slow. The surface potential at the electret center is plotted as a function of time for this calculation along with measured points for the same configuration in Fig. 4.8. The variation of the measured points from the straight line is due to the timer error on the Faxitron X-ray source. From this graph it is evident that, in reality, charging is linear with time until the surface potential nearly equals the applied potential, which indicates that the assumption of multiplicative combination leads to a severe under-estimation of gross chamber efficiency. For this reason, we now believe that a calculation of efficiency should be applied only at the cell in which a particular group of ions originates, and allow whatever percentage of charge that escapes the cell to be drawn unhindered to the termination of the electric field line which it follows. This is so because the neighboring cell into which a group of ions is pulled also has ions being generated within it, and those ions entering are surplus and are likely not to recombine. This assumption permits the determination of a collection efficiency averaged over all of the cells that more closely resembles the collection efficiency calculated for the entire chamber.

4.4 First Model

After arriving at an acceptable solution for the electrostatic potential as a function of \( r \) and \( z \), a calculation must be performed to determine the placement of electric charge on the electret surface, for which the assumption is made that the charge follows the trajectories of the electric field lines. In the first attempt at accomplishing this, the procedure was to mathematically determine, using the calculated array of electrostatic potentials, the piece-wise straight trajectories of electric field lines originating midway between points 1 mm apart on the electret surface, with the trajectories proceeding in steps of variable length, but with a \( z \)-component of 0.25 mm. A calculation is then performed to determine the area
Figure 4.7 Charge calculations for a chamber with an 8 mm air-gap and 200 V applied potential. Curves obtained at 1 second intervals. Second model was used.

enclosed by: (1) the adjacent field lines in the radial direction, and (2) adjacent lines of constant z in multiples of 0.25 mm in the axial direction. The area is weighted by a value of ion density (assumed for this model to be equal to 1 everywhere) and the quantity of charge that results is added to the charge trapped on the electret surface between the points of origin of the two electric field lines. This is depicted in Fig. 4.9.

The area in the \( r - z \) plane that is associated with the trajectories emanating from the edges of the \( j \)th radial element, \( j = 0...r_{\text{max}} \), along the electret are thus calculated as a summation of area elements \( dA_j(i) \), shown in Fig. 4.9 for \( j = 1 \) and \( i = 0 \). The trajectories of the segments of electric-field lines shown
Figure 4.8 Comparison of model assuming multiplicative combination of collection efficiency with measured points.

in Fig. 4.9 are defined by

\[ \gamma_1 = \arctan \frac{2\Delta z(\phi[\text{trunc}[r_j(z)/\Delta r] + 1], i_1) - \phi[\text{trunc}[r_j(z)/\Delta r], i]}{\Delta r(\phi[\text{trunc}[r_j(z)/\Delta r], (i + 1)] - \phi[\text{trunc}[r_j(z)/\Delta r], (i - 1)])} \]  

(4.17)

and

\[ \gamma_2 = \arctan \frac{2\Delta z(\phi[\text{trunc}[r_j(z)/\Delta r] + 2], i_1) - \phi[\text{trunc}[r_j(z)/\Delta r] + 1], i]}{\Delta r(\phi[\text{trunc}[r_j(z)/\Delta r] + 1], (i + 1)] - \phi[\text{trunc}[r_j(z)/\Delta r] + 1], (i - 1)])} \]  

(4.18)

where the denominators are the local z-components of the electric field, the numerators are the local \( r \)-components, trunc indicates a truncation function, \( \gamma_1 \) is the angle between the local electric-field and the positive \( z \) axis at the side of the radial element which is closest to the origin, and \( \gamma_2 \) is the angle between the local electric-field and the positive \( z \) axis at the side of the radial element which is farthest from the origin.
Figure 4.9 A depiction of the calculation of charge deposition at the $j = 1$ point.
An increment of surface potential \( \frac{\partial \phi(r)}{\partial t} \Delta t \) is then calculated as

\[
\frac{\partial \phi(r)}{\partial t} \Delta t = C \sum_{i=1}^{a} \prod_{k=1}^{i} \{ f_j(k) \} dA_j(t),
\]

(4.19)

where \( f_j(k) \) is the collection efficiency at the \( k \)th point along the trajectory originating from the \( j \)th element along the electret radius. The constant of proportionality, \( C \) is a number calculated from information about the desired nominal charge rate, i.e. the change in surface potential per time step \( \Delta \phi_n \)—typically 10% of the applied potential, and is proportional to the rate of generation of charge carriers. The constant can be calculated by the user as \( C = \frac{\Delta \phi_n}{a(\Delta \tau)(\Delta r)} \).

This constant will provide a change in surface potential roughly equal to \( \Delta \phi_n \) at the end of every time step, but it does not account for such things as inefficient ion collection, or edge effects, due to which the rate of charging may slow at some places on the electret surface.

With the addition of the incremental charge density expressed by Eq. (4.19), the program returns to the calculation of the electrostatic potential throughout the solution space under the new conditions imposed by the recent addition of charge to the electret surface, and the entire process is repeated until the change in surface potential between iterations falls below a given threshold of 10\(^{-5} \) %, for example.

To model the discharge of the electret with the same algorithm, a simple modification was required in which the value of the externally applied potential is set to zero, and a uniform charge density is placed at the electret surface.

Calculation of electrostatic potentials took place in a grid containing 5500 square elements: 100 in the \( z \) direction and 55 in the \( r \) direction, 1 element occupying 0.01 cm\(^2 \). Because of the circular symmetry of the system, only points in one \( r-z \) plane where \( r \geq 0 \) were considered. The radius of the electret being modeled was 2.5 cm, and was therefore given a radius of 25 model elements. An air-gap of either 0.2 or 0.8 cm was used in the calculations, and a polymer
thickness of 0.0254 cm was assigned. Convergence was evaluated by tracking the average change in potential $\overline{\Delta V}$ over all points in the solution space. With the number of iterations $n = 1000$, $\overline{\Delta V}/V_0 < 10^{-7}$.

### 4.5 Second Model

#### 4.5.1 Ion Generation

Results from the first model were encouraging, but there were some obvious inadequacies that had to be addressed in the model, in the measured data to which these results were compared and even in the method of comparison. There were such problems as: the inability of the trajectory-tracing code to deal with electric field lines that double back or turn sharply, the assumption of uniform ion density throughout the chamber, the assumption that local efficiencies combine multiplicatively as charge proceeds along electric-field lines, the fact that measurements were taken only to a radius of 16 mm, and the fact that there was a line-spread-function of the measurement system which needed to be accounted for in comparing calculations with measured data.

In an effort to remedy these problems, it was decided that, in the model, the space between the electrodes would be divided into a number of small cells of fixed size and that rather than have the electric field trajectories proceed in steps of variable length originating at the electret surface, it would be better to have them originate at each cell, proceed in fixed steps of a given length and terminate on the electret surface, as is depicted in Fig. 4.10. This simplified much of the problem of depositing charge.

Since the charge that manages to escape its cell of origin without recombining is a quantity of excess charge in the cells through which it passes, it was decided that a collection efficiency calculated once at the cell of origin would be applied to each packet of charge and that transport would thereafter be unhindered to the
point of termination, on whatever air/solid surface it encountered. If the surface of termination was electret in nature, the packet of charge would be deposited at the nearest discrete point on the radius of the electret. This is illustrated simply in Fig. 4.10.

**Single Scatter Ion Distribution**  Another consideration was the estimation of the quantity of charge liberated in a particular cell by the ionizing radiation. In the past we had avoided the problem, assuming that the ions were evenly distributed throughout the chamber. We now use one of two methods to estimate ion distribution in the REIC. The first method we will call the Single Scatter Ion Distribution (SSID) technique, which requires knowledge of the spectrum of the radiation beam. The calculated spectrum\(^{14}\), for a 100 kVp beam filtered by 0.28 mm of beryllium and 3 mm aluminum and shown in Fig. 4.11, has an average energy of 46 keV, is assumed to impinge on a small sample of scattering material,
and is operated on by the known angular scattering distributions for the Photo-electric and Compton effects\textsuperscript{13,15}, producing a distribution of scattered electrons with various initial energies and scattering angles. The differential photo-electric
scattering cross-section $\frac{\partial \psi_p}{\partial \Omega}$ is expressed as

$$\frac{\partial \psi_p}{\partial \Omega} \propto \frac{\sin^2 \theta_e \cos^2 \varphi}{(1 - \beta \cos \theta_e)^4},$$  \hspace{1cm} (4.20)

where $\theta_e$ is the angle between the velocity of the scattered electron and that of the incoming photon, $\varphi$ is the angle between the velocity of the scattered electron and the direction of polarization of the impinging photon, $\Omega$ is the solid angle defined by $\theta_e$, and $\beta$ is defined as

$$\sqrt{1 - \frac{1}{(E/E_o + 1)^2}},$$  \hspace{1cm} (4.21)

where $E$ is the energy of the impinging photon and $E_o$ is the rest energy of an electron. The scattering angles are shown in Fig. 4.12.

The direction of polarization is completely arbitrary, since the impinging X-rays are incoherent, so the cross-section expressed in Eq. (4.20) is averaged over the angle $\varphi$, resulting in

$$\frac{\partial \psi_p}{\partial \Omega} \propto \frac{\sin^2 \theta_e}{(1 - \beta \cos \theta_e)^4}.$$  \hspace{1cm} (4.22)

Similarly, the Compton scattering cross-section is expressed as

$$\frac{\partial \psi_e}{\partial \Omega} \propto \frac{1 + \cos^2 \theta_\gamma}{2} \left[ 1 + \frac{\gamma^2(1 - \cos \theta_\gamma)^2}{(1 + \cos^2 \theta_\gamma)(1 + \gamma(1 - \cos \theta_\gamma))} \right],$$  \hspace{1cm} (4.23)

where $\theta_\gamma$ is the angle defined between the vector of the scattered photon and the incoming photon, and $\gamma$ is the ratio of photon energy to electron rest energy.

The angle of electron scattering is related to $\theta_\gamma$ by the expression:

$$\cos \theta_e = (1 + \gamma) \left[ \frac{1 - \cos \theta_\gamma}{2 + \gamma(\gamma + 2)(1 - \cos \theta_\gamma)} \right]^{1/2}.$$  \hspace{1cm} (4.24)

The angles discussed are shown in the illustration of Compton scattering in Fig. 4.13.
A scattering plane surrounding one small scattering centre was divided into 180 angular elements. For each element, the relative distribution of scattered electrons from both the Compton and photo-electric effects was calculated using Eqs. (4.22), (4.23) and (4.24). The relative numbers of scattered photo-electrons and Compton electrons is determined by the ratio of the published\textsuperscript{13} total cross-sections for the two interactions at the average energy of 46 keV.

A table of stopping powers\textsuperscript{16} is consulted within the program to determine the ionization density caused by recoil electrons as they proceed in small increments.
through the surrounding air for each element of solid angle. For simplicity, the recoil photon, if it exists, is assumed to be transported away and the trajectories of all recoil electrons are assumed to be straight lines. In this manner, a cloud of ion density surrounding a single scattering center is calculated. The results of this calculation are shown in Fig. 4.14 in the form of contours denoting relative ion density. We then numerically convolve this cloud around the inner surface of the
Figure 4.14 Contour plot of an ion distribution calculated around a small target situated at the tip of the arrow which represents the photon-beam, using the SSID technique. Ion densities are normalized to a value of 1.
REIC to produce the final ion distribution, shown in Fig. 4.15. No consideration is given to the relative number of scattering events at each surface point or to those events occurring in the bulk of the scattering material. Also, we assume for simplicity that no photon scattering events occur in the air of the REIC.

Isotropic Scattering In the second method, which we will call the Isotropic Scattering (IS) technique, we assume that the creation of ions due to scattering from a single target point is isotropic, falling off as \( r^{-2} \), and we numerically convolve this function around the inner surface of the REIC to produce the density distribution shown in Fig. 4.16. The distribution resulting from the two methods differ because of the forward scattering accounted for in the SSID technique, but the difference seems to have little effect on the distribution of charge as it is trapped on the surface of the electret.

4.5.2 Charge Deposition

The area between the electrodes is divided into two-dimensional cells measuring 0.025 cm axially (\( z \)) and 0.025 cm radially (\( r \)), and the surviving ions produced within each cell are placed on the electret surface according to the trajectory of the electric field line originating at that cell. If the electric field line terminates on a surface that is not an electret surface, the associated ions are discarded.

The equation for the deposition of charge can now be stated as

\[
\frac{\partial \phi(r)}{\partial t} \Delta t = C \sum_{i=1}^{a} \sum_{j=1}^{r} \rho_{i,j} f_{i,j} \Delta A \delta(i - i^*, j - j^*),
\]

(4.25)

where \( \rho_{i,j} \) and \( f_{i,j} \) are the ion density and collection efficiency respectively in cell \( i,j \), \( \Delta A \) is the area of the cell, \( i^*, j^* \) are the locus of points defined by the electric field lines originating within 0.5 mm of point \( r \) on the electret radius, \( \delta \) is the Kronecker Delta function equal to 1 when \( i \) and \( j \) are equal to \( i^*, j^* \) and 0 otherwise, and \( C \) is a constant of proportionality used to control the rate of the simulated charging, as was defined in Eq. (4.19).
Figure 4.15 Ion density in REIC as calculated using the SSID technique. Because of forward scattering, the entrance surface has a higher ion density than the exit surface. Above is a contour plot of same density.
Figure 4.16 Ion density in REIC as calculated using the IS technique.
After all cells have had their surviving ionic contents deposited on an inner REIC surface (electret or otherwise), the electric field is recalculated for the new charge condition of the electret surface, and the process of ion deposition is continued.

The problem of comparing calculated charge profiles with measured ones was solved by convolving the calculated profile with the 0.38 cm Gaussian curve described in Section 3.4. This function is thought to be the line-spread-function for the measurement of a circular edge of radius 2.5 cm with the electrostatic probe, scanning at the velocity used in these experiments.

The programs that were used for generating ion distributions, calculating the electric field and depositing charge are all written in Pascal and run on a 386-PC.

4.6 Results and Discussion

4.6.1 Measured and Modeled Charge Distributions

The dots in Fig. 4.17 show the results from measurements obtained during electret charging to a potential of 200 V, at an air-kerma rate of approximately 2 mGy/sec with (a) a 2 mm air-gap, and (b) an 8 mm air-gap. The curves were obtained at 5 second intervals in (a) and 1 second intervals in (b), starting from the onset of irradiation. The two sets of distributions are similar though those obtained when \( a = 2 \) mm are consistently more uniform than those obtained when \( a = 8 \) mm. If it were given enough time, the REIC with the 8 mm air-gap would eventually achieve a uniform charge distribution, but the time needed for this is on the order of several hours, as the electric-field resulting from the undercharged edges is very weak and collection of charge is inefficient. A set of results corresponding to the discharge of the electret are illustrated by the symbols shown in Fig. 4.18 again for (a) \( a = 2 \) mm, and (b) \( a = 8 \) mm. It should be noted that, because of timer-error and output fluctuations associated with the X-ray source,
Figure 4.17 Calculated charge distributions (solid lines) compared with measured distributions (dots) for charging with a chamber radius of 35 mm, an electret radius of 25 mm, an external potential of 200 V and an air-gap of (a) 2 mm and (b) 8 mm. Time intervals between curves are (a) 5 seconds and (b) 1 second.
Figure 4.18 Calculated charge distributions (solid lines) compared with measured distributions (dots) for discharging with (a) a 2 mm air-gap and (b) an 8 mm air-gap. Time intervals between curves are (a) 5 seconds and (b) 1 second.
those measurements spaced closely in time have a large fluctuation in incremental charge from one measurement to the next. This is most noticeable in the case of the 8 mm air-gap for which 1 sec exposures were used and for which the change in surface potential between scans may be 20 V at one time and 25 V at another.

As mentioned above, the electret charge distribution is sensitive to scatter that originates near the electret. Having observed this, and as described above, we were able to reduce scatter by replacing connecting wires with aluminum strips and thus obtain more uniform distributions in comparison to those which we reported previously\(^7\), most noticeably in the case of charging with a 2 mm air-gap, for which we have eliminated excess charging near the edge. As well, it was determined that a systematic error was responsible for the apparently premature cessation of charging in the case of the larger air-gap. The measurements shown in Fig. 4.17 indicate that when charging with a smaller air-gap, charge densities are uniform, falling off rapidly at the edge of the electret indicating that the chamber is insensitive to edge effects at small air-gaps. The distributions obtained with a larger air-gap are not as uniform, being rounded near the edge, due, as was discussed, to the convergence of electric field lines on the polarizing electrode. It seems also that for both air-gaps, charging continues at a steady rate until the electret potential nearly equals the applied potential.

A typical result from the calculation of charge distributions during electret charging is illustrated in Fig. 4.19 for (a) an ion distribution generated via the SSID method and (b) an ion distribution estimated by the IS method. These distributions have not been convolved with the system’s line-spread-function. As the difference observed in the calculation of charge is minimal, we chose to work primarily with the simpler IS approximation. In Fig. 4.17 the post-convolution results of charging calculations for a chamber with two different air-gaps are shown in comparison to the corresponding measured distributions. Agreement between measurement and
Figure 4.19 *Comparison of charge distribution calculations as affected by the choice of ion distributions for a chamber radius of 35 mm, an electret radius of 25 mm, an external potential of 200 V and an air-gap of 8 mm.*

model is very good. In Fig. 4.18 the corresponding post-convolution calculations of the discharge distributions are shown in comparison with measured distributions. Agreement is not as good for discharging as for charging, since the gradient of the
measured charge density seems to be steeper than the calculated gradient in the case of the 8 mm air-gap and the opposite is true for the 2 mm air-gap, possibly owing to the electric-field lines which we calculate as being less well behaved, diverging away from the electret and often terminating on the plastic surface of the REIC. It is possible that by taking into consideration the charge-storage characteristics of the Lucite and polystyrene surfaces in the chamber we may be able to improve the predicted distributions. It would then also be necessary to consider the effects of measurement on the surface-charge conditions of the material surrounding the electret because a grounded conducting ring is placed around the electret surface when the surface charge is measured.

4.6.2 The Electric Field

The electric field data generated by the model is illustrated in Figs. 4.20 and 4.21 in which the thick, horizontal line represents the electret surface, and the advancement of time is indicated by the arrow to the left of each set of figures. The first series demonstrates the evolution of the electric-field in the REIC as a 0.025 cm Teflon (FEP) electret is charged to an external potential of 200 V with a 0.8 cm air-gap, with the initial field on the top of the page and the final field at the bottom. The second series represents discharge under the same configuration. The region shown in these figures is a radial plane beginning on the left-hand side at the axis of the chamber and traversing the air-gap and Lucite spacer ring which lies on the right hand side. A discontinuity in the normal component of the electric-field can be seen at the air/Lucite interface. The electric field lines leaving the electret surface near its edge tend to converge toward the polarizing electrode while the electret is being charged, the effect being more pronounced as the charging advances. The electric field lines above the region of the electret
having a radius of less than about 1.0 cm are unaffected by the charging.

Conversely, as the electret is discharged, the electric field lines diverge from the electret surface. Again the divergence increases as the discharging proceeds, but a much larger region of the electret is affected by the discharging process than by the charging. For dosimetric purposes, this type of diagram can be used to determine what, if any, collector size is acceptable for reading the dosimeter by discharge techniques, as discussed in Chapter 7. For this reading method, the collector must be large enough to give a clean signal though small enough to permit an acceptable range of linear response. Barring collection efficiency problems, the configuration depicted in Fig. 4.21 would give a linear response until the electret had lost roughly half of its charge, if the collector had a radius that was one half of the electret radius. This is evident because of the warping of the electric field lines that occurs. Reading the electret with an electrostatic probe would permit the dosimeter to have a greater range, since it would require a signal only from a small central region of the electret.
Figure 4.20 A series of calculated electric-field lines for the charging of a 0.025 cm Teflon (FEP) electret to 200 V in a chamber with a 0.8 cm air-gap. Time advancing in steps of relative units.
Figure 4.21 A series of calculated electric-field lines for the discharging of a 0.025 cm Teflon (FEP) electret initially charged to 200 V, in a chamber with a 0.8 cm air-gap. Time advancing in steps of relative units.
References


# Chapter 5

**Radiation Induced Conductivity**

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5.1 Introduction

As we have discussed in previous sections, electret ionization chambers (EICs) have been used for radiation dosimetry\textsuperscript{1-3} and for electret production\textsuperscript{4-7}. An EIC differs from a regular parallel-plate air-filled ionization chamber in that an electret (a dielectric film with a surface charge) covers the collecting electrode. In a conventional EIC, the electret can be charged by a variety of means, the most popular being corona discharge\textsuperscript{8}. When the EIC is used in the field as a radiation dosimeter, it does not require an external potential because the trapped charges on the electret provide the electric field for the sensitive volume between the collecting and polarizing electrodes. Exposure to radiation produces ions in the air gap which drift towards the electret to neutralize the charge on the electret surface. Within a certain range, the air-kerma is related to the difference between the original electret charge and that remaining after the irradiation.

The electret in a radiation charged electret ionization chamber (REIC)\textsuperscript{1,4}, however, is charged by irradiating the chamber while simultaneously applying an external potential between the polarizing and collecting electrodes. Ions produced in the air gap drift in the applied field and become trapped on the surface of the insulator. These charges produce their own electric field which proportionally decreases the effective electric field across the chamber. It was believed that when the process is initiated in a chamber under saturation conditions, the current measured at the collecting electrode is equal to the saturation current and remains constant until the effective electric field decreases below saturation values, when it subsides accordingly. It was also thought that eventually, sufficient charges are trapped on the electret surface to produce a uniform charge distribution on the electret with a surface potential that is equal to the externally applied potential. At this time, the effective electric field across the chamber and the collecting current should equal zero though irradiation may continue.
Time-dependent expressions for electric field and current during the charging and discharging processes were obtained\(^6\) without consideration of the small contribution from the displacement current, and more importantly, without consideration of radiation-induced conductivity (RIC) within the bulk of the electret insulator resulting from the electron-hole pairs produced by the irradiation. The latter effect would allow charges trapped on the surface of the electret to be pulled through the bulk, thereby reducing the amount of charge on the electret, and affecting the charging/discharging characteristics of the REIC. These expressions were acceptable because they were developed for low electric fields, e.g., 2.5 kV/cm where RIC effects are minimal, and for Mylar as the electret material, which is a material that inherently exhibits low RIC. However, another electret material Teflon polyfluoroethylene propylene (FEP), can be used as the electret material because it exhibits superior charge-retention capabilities. Unfortunately, it has been shown that at steady-state\(^9-11\) Teflon (FEP) also exhibits larger RIC than Mylar.

We will present measurements of RIC for Teflon (FEP) at non-steady state conditions from which we have developed a dynamic expression for the REIC which accounts for the displacement current, and for RIC as functions of air-kerma rate and electric field within the electret. Limitations of the use of the Teflon (FEP) REIC due to RIC effects will then be described.

### 5.2 Radiation-Induced Conductivity in Teflon (FEP)

In charging REICs with Mylar electrets\(^4\), the collecting current approaches zero as the electret surface potential approaches the value of the externally applied potential \(V_0\). This effect is shown schematically as the solid curve of Fig. 5.1 (b). However, as shown by the dashed curve of the same figure, we found that for REICs with Teflon (FEP) electrets, the collecting current never reaches zero as the electret surface potential approaches \(V_0\). We believe that this residual current
Figure 5.1 (a) Schematic of (i) the REIC and (ii) the polymer sandwiched between two electrodes. (b) Schematic of the current curves obtained with the REIC when charging for a polymer exhibiting very minimal RIC (solid) and one exhibiting larger RIC effects (dashed). The residual current believed to be due to RIC is also shown.
which remains constant while irradiation continues is due to RIC. In Fig. 5.2, we show the effects of changing the external potential $V_o$ on the residual RIC. The REIC was maximally charged at the respective $V_o$ followed immediately by discharge (i.e., $V_o = 0$) resulting in an initial current density that is equal in magnitude but opposite in sign to the initial charging current density. It is important to note that the measured current density at the onset of each charging cycle is constant irrespective of the external potential, but that the magnitude of the residual RIC tail observed at the end of the charging process increases with $V_o$. There is negligible residual tail during the discharging process because the electric field across the polymer is zero, and, as we will discuss below, the RIC current is a function of this electric field.

Gross\textsuperscript{10} found that X-ray induced conductivity in Teflon (FEP) typically exhibits an increase at the onset of irradiation, followed by a peak and a subsequent slow decline. A system of rate equations\textsuperscript{10,12} can be used to predict RIC:

\begin{align}
\frac{dn}{dt} &= \delta - \alpha n m - n/\tau + n_t/\tau^* \\
\frac{dn_t}{dt} &= n/\tau - n_t/\tau^* \\
\frac{dm}{dt} &= \delta - \alpha n m,
\end{align}

where $n$ is the concentration of free and shallow-trapped charge-carriers (thought to be holes, cm$^{-3}$), $n_t$ is the concentration of deep-trapped carriers (cm$^{-3}$), $\delta$ is the rate of generation of carrier concentration (cm$^{-3}$s$^{-1}$), $\alpha$ is a trap-modulated recombination coefficient (cm$^{-3}$s$^{-1}$), $m$ is the concentration of trapped electrons (cm$^{-3}$), $\tau$ is the characteristic hole deep-trapping time (s), and $\tau^*$ is the corresponding detrapping time (s). The solution of these equations requires a numerical method with computation time being proportional to the desired number of temporal points. The RIC within the polymer is then calculated as

\begin{equation}
g(t) = en(t)\mu,
\end{equation}
where \( n \) is calculated from Eqs. (5.26), \( \mu \) is the trap-modulated mobility of holes in the valence band in units of \( \text{cm}^2\text{V}^{-1}\text{s}^{-1} \), and \( e \) is the electronic charge. Figure 5.3(a) shows a typical result of our fitting of Eqs. (5.26) and (5.27) to data obtained using the configuration shown in Fig. 5.1 (a(ii)). Our seed values for the parameters \( \delta, \alpha, \mu \) and \( \tau \) were obtained from Ref. 10 and marginally modified by our algorithm to provide our best fit to data. Normally the detrapping time \( \tau^* \) is

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{current_densities.png}
\caption{Current densities as measured across the REIC during charging and discharging cycles with varying \( V_0 \)'s.}
\end{figure}
Figure 5.3 (a) and (b) Typical values of calculated and measured RIC of Teflon (FEP). (c) Experimentally determined values of exponents used in calculation of RIC in Eqs. (5.30) & (5.32)
so much greater than the trapping time $\tau$ that in the region considered with these measurements, hole detrapping is not yet observable: it is only observable at steady state conditions occurring at times $t$ greater than $200$ s. Given the assumption that these equations are valid, despite not considering space-charge effects, they fit our data reasonably well. We conclude that space charge effects can safely be ignored in the treatment of this subject.

Other empirical relationships of RIC have been determined at steady state conditions. RIC varies with electric field $^{9-11}$ $E_p$ in the polymer as

$$g(E_p) = g_{E_p, K_0} (E_p/E_{p_0})^{\Delta_1},$$

and with air kerma rate $^{13-16}$, $\dot{K}$ as

$$g(\dot{K}) = g_{E_{p_0}, K_0} (\dot{K}/\dot{K}_0)^{\Delta_2}$$

respectively, where $g_{E_{p_0}, K_0}$ is the conductivity measured at an air-kerma rate of $\dot{K}_0$, and an electric-field strength of $E_{p_0}$. The terms $\Delta_1$ and $\Delta_2$ are constants with $0 \leq \Delta_2 \leq 1$, and $\Delta_1 = 0.3$. Both exponents depend on duration of irradiation, electret material and temperature of the electret. The air-kerma rate dependence in Eq. (5.29) can be stated as dose-rate dependence, which is the more commonly used quantity, but this does not alter the expression since the two are linearly related. Since we also deal with ionization in air in this work, we wish to be consistent in our expression of radiation effects in matter by remaining with the air-kerma quantity.

Although RIC at steady state is adequately described by Eqs. (5.28) and (5.29), RIC conductivity for non-steady conditions obtained at onset of irradiation have not been fully documented, and one must revert to Eqs. (5.26) and (5.27) to obtain some kind of approximation to the fit. It is, however, difficult to determine RIC as a function of $E_p$ and $\dot{K}$ from this set of equations. We thus proceeded to find
an alternate method of representing steady- and non-steady- conditions of RIC as function of $E_p$ and $\dot{K}$.

We have measured RIC at onset of radiation (i.e., under non steady-state conditions), and found that the parameters $\Delta_1$ and $g_{E_{p0}, \dot{K}_o}$ are functions of time at these conditions. We can rewrite Eqs. (5.28) and (5.29) in the following time-dependent form:

$$g(t, E_p, \dot{K}) = g_0(t)(E_p/E_{p0})^\Delta_1(t)(\dot{K}/\dot{K}_o)^\Delta_2,$$  \hspace{1cm} (5.30)

replacing $g_{E_{p0}, \dot{K}_o}$ with $g_0(t)$. The conductivity $g_0(t)$ was measured at a constant air-kerma rate $\dot{K}_o$ and electric field $E_{p0}$ for 120 s of irradiation. We found that the following equation

$$g_0(t) = g_{\text{max}} \left( \frac{t}{t_1} + \frac{t_2}{t} + \eta \right)^{-1},$$  \hspace{1cm} (5.31)

though entirely empirical, provides an adequate fit to the data through the proper adjustment of the parameters $t_1, t_2$ and $\eta$. The constants $t_1$ and $t_2$ appear to depend on the rate of detrapping and on the rate of trap filling, respectively and $\eta$ is an offset. A typical fitting produced by this function is shown in Fig. 5.3(b), and appears to offer a single equation fit that allows an analytic manipulation of the function, and that is comparable to the fit achieved by Eqs. (5.26) and (5.27) shown in Fig. 5.3(a). In the region of $t < 10$ s, Eq. (5.31) seems to even surpass the fit of Eqs. (5.26) and (5.27).

Current versus time curves were obtained for several electric fields, from which conductivity versus electric field was plotted for different points in time after onset of irradiation. A power function with a particular exponent was fitted to each of the plotted curves. We used the following empirical equation

$$\Delta_1(t) = A[1 - B \exp(-t/t_{01})]$$  \hspace{1cm} (5.32)

to fit the exponents as a function of time. It was found that for steady state conditions ($t > 100$ s), the measured values of $\Delta_1$ agree with those predicted by
In a similar fashion, values for $\Delta_2$ were obtained through measuring current versus time curves for several air-kerma rates. It was found that $\Delta_2$ is independent of time. For a typical case of $K_o = 44$ mGy/s and $E_{p.o.} = 37.4$ kV/cm depicted in Fig. 5.3 (a) and (b), the following values for the parameters were determined: $A = 0.03084$; $B = 4.35$; and $t_{01} = 22.436$ s.; $\Delta_2 = 0.67$ to obtain the fitted relationships shown in Fig. 5.3 (c). It has been shown that $\Delta_2$ can vary from 0.5 to 1.0, depending on the electret material.$^{13}$

5.3 Charging Dynamics of the Radiation-Charged REIC

We are now in a position to insert RIC effects within the relationships that govern the charging dynamics of the radiation-charged REIC. It will be recalled from Chapter 2 that the current density measured in a REIC during irradiation can be expressed as:

$$j = \varepsilon_0 \varepsilon_a \varepsilon_{p,} - \varepsilon_{p,} \varepsilon_{p,} + j_a,$$

(5.33)

where the first term represents the displacement current density. While the electric field in the air gap of a REIC during the charging is:

$$E_a(t) = \frac{V_o \varepsilon_0 \varepsilon_p - p\sigma(t)}{\beta p},$$

(5.34)

where $V_o$ is the external potential applied to the polarizing electrode, $\varepsilon_p$ is the dielectric constant of the polymer electret, $p$ is the thickness of the polymer, $\sigma(t)$ is the electret surface charge density, and $\beta = \varepsilon_0 (p\varepsilon_a + a\varepsilon_p)/p$, where $a$ is the height of the air gap. Through the laws of Gauss and Kirchoff, the electric field across the polymer can be expressed as a function of the electric field in the air gap as follows

$$E_p = [V_o - a E_a(t)]/p.$$

(5.35)

The parameter, $\sigma(t)$ can now be expressed as

$$\sigma(t) = \sigma_a(t) - \sigma_p(t),$$

(5.36)
where $\sigma_a(t)$ is the surface charge density that has accumulated on the electret by conduction through the air-gap after $t$ seconds of charging, and $\sigma_p(t)$ is the amount of charge density that has been removed from the surface due to RIC in the same amount of time. Differentiating Eq. (5.34) with respect to time and using Eq. (5.36) leads to

$$\frac{dE_a}{dt} = \frac{d\sigma_p}{\beta dt} - \frac{d\sigma_a}{\beta dt}. \tag{5.37}$$

Finally, substituting the current density, $j = \frac{d\sigma}{dt}$, into the above equation results in the following expression:

$$\frac{dE_a}{dt} = \frac{j_p}{\beta} - \frac{j_a}{\beta}, \tag{5.38}$$

where $j_p = gE_p$ and $g$ is given by Eq. (5.30). The term $j_a$ can be represented as the full saturation curve of a parallel-plate chamber, with the difference that the electric field across the chamber is continuously changing in time due to the change in $\sigma_a$ and the subsequent change in effective electric field $E_a$ across the air gap. We can use a simple approximation to the full saturation curve of parallel-plate chambers $^{17,18}$:

$$j_a = j_{sat} \tanh \left[ E_a/R(a_{j_{sat}})^{1/2} \right], \tag{5.39}$$

where $j_{sat} = \kappa \dot{K}a$ is the saturation current density, or the current density corresponding to maximum ion collection, $\kappa = 3.536 \times 10^{-11} \text{ C/cm}^3\cdot\text{mGy @ NTP}$, is a constant of proportionality and $R = 1.24 \times 10^6 \text{ V/(Amp-cm)}^{1/2}$ is an empirically derived constant which depends on mobilities and recombination coefficients of the air ions. Although the expression for collection efficiency used here, i.e. $\tanh \left[ E_a/R(a_{j_{sat}})^{1/2} \right]$, differs from that used in Eq. 4.5, it is just as accurate and requires less computation time. Using Eq. (5.38) with Eqs. (5.35) and (5.39) results in the following first order non-linear differential equation:

$$\frac{dE_a}{dt} = \frac{gE_p}{\beta} - \frac{j_{sat}}{\beta} \tanh \left[ E_a/R(a_{j_{sat}})^{1/2} \right], \tag{5.40}$$
which when substituted into Eq. (5.33) gives

\[ j = \frac{\varepsilon_0 \varepsilon_a}{\beta} \left[ g E_p - j_{sat} \tanh \left( E_a / R(a j_{sat})^{1/2} \right) \right] + j_{sat} \tanh \left( E_a / R(a j_{sat})^{1/2} \right). \]  

(5.41)

\( E_a \) in Eq. (5.40) or (5.41) was calculated as a function of time with the use of a fourth order Runge-Kutta technique.

Once the REIC is fully charged, \( E_a \approx 0 \), never equalling zero exactly because of RIC. For example, if \( V_0 = 400 \) V, \( a = 0.4 \) cm, and \( j_{sat} = 55 \) pA cm\(^{-2} \), the solution of Eq. (5.41) for the residual current predicts a current density of 5 pA cm\(^{-2} \). Substitution of this value into Eq. (5.39) results in a minimum electric field in the air-gap of 0.53 V cm\(^{-1} \), an extremely low value. One can calculate the effect of this residual electric field on the maximum attainable charge density. According to Eq. (5.34), the surface charge density corresponding to a residual electric field of 0.53 V cm\(^{-1} \) is 2.9405 nC/cm\(^2 \), while the charge density predicted for no residual field is 2.9407 nC/cm\(^2 \).

For the discharge of the REIC, the external potential is removed \( (V_0 = 0) \), and the surface charge density expressed by Eq. (5.34) for \( E_a = 0 \) is substituted into Eq. (5.34) to obtain the initial electric field across the air gap:

\[ E_a = -V_0 \varepsilon_p / (\rho \varepsilon_a + a \varepsilon_p). \]

Equations (5.41) and (5.40) are then evaluated to determine the current density behavior during the discharging process.

Typical measured and calculated current density curves for the charging and discharging of a REIC are shown in Fig. 5.4 (a). One should note that the discharging curve has been placed directly underneath the charging curve to better demonstrate the differences and similarities between the two curves. Calculated current density curves expected in the absence of RIC are also shown for sake of comparison. At the onset of charging, the current density is 52 ± 1 pA cm\(^2 \), slightly less than the saturation current density of 54.5 pA cm\(^2 \), as predicted by Eq. (5.41). For approximately 50 s after the onset of charging, the current
Figure 5.4 (a) Typical measured and calculated current densities for charging and discharging in a REIC with $a = 0.4$ cm, $V_0 = 400$ V, $p = 0.025$ cm, and $\dot{K} = 2.2$ mGy/s. (b) Calculated real current density flowing through the electret during the charging and discharging processes.
density is modulated by the changes in $gE_p$. The range of these changes is calculated as being on the order of 5 pA cm$^{-2}$, and when weighted by the ratio of $\frac{\varepsilon \sigma}{J}$ in Eq. (5.41) it is reduced to a value of 0.1 pA cm$^{-2}$. This low value leads us to expect that the measured time dependence of the current curve in this period is due to something other than strict RIC, very possibly due to changes in the trajectories$^{19,20}$ of electric-field lines as the electret is charged, as discussed in Chapter 4. We do not expect the discrepancy between the theoretical and measured time-dependent current-densities to be due to error in the prediction of radiation induced conductivity. Rather, it appears that the one-dimensional nature of the treatment of the current density is at fault, and that the discrepancies can be eliminated through accounting for the finite extent of electret and electrodes. It seems likely that a larger guard-ring would have decreased these errors by more closely approximating a one-dimensional system, thus prolonging the time over which the sensitive volume remains constant. After 55 s of charging, $E_a$ is reduced sufficiently to cause the air current-density to fall rapidly. Because of the RIC, $E_a$ never reaches zero, and a residual current flows across the air-gap to compensate for the current flowing through the dielectric. There is good agreement between the calculated and measured steady state current densities in the maximally charged REIC. Another effect of RIC on the charging current curve is to increase the duration of saturation conditions in the air-gap, causing the current density to fall several seconds later than it would in the absence of RIC. This is to replace the charge that is lost by conduction through the polymer while the REIC is charging and $j_a$ is at its maximum.

At the onset of radiation during discharge, the current density is equal and opposite to the initial charging current density. In this process, the fall of the current density is hastened somewhat by the effects of RIC. This is due to charge flowing away from the electret surface through both the air-gap and the dielectric.
The effect is not as marked as it is observed to be during charging because the value of the charge transported through the dielectric, $\int_0^t g E_p dt$ is smaller for discharging than it is for charging.

The calculated current density through the polymer, $j_p = g E_p$ is shown in Fig. 5.4 (b) for both the charging and discharging stages. The initial peak of the charging $j_p$ current density is due to $g_{max}$ of Eq. (5.31), and the conductivity $g$ falls as the electric field $E_p$ increases linearly until approximately 50 s when the maximum field has been reached. The continuing decrease in $g$ causes the resulting current density $j_p$ to decrease eventually reaching a constant value.

A similar peak is obtained when the REIC is discharged, followed by a constant decrease of current due to a decrease in $E_p$. However, the peak is not observed when the REIC is discharged immediately following the charging process. In this situation RIC has already reached the steady state conditions, and what is observed (see Fig. 5.4 (b) ) is the steady decline of $j_p$ due to the linear decrease of $E_p$.

5.4 Practical use as a Dosimeter

One can analyze the impact of RIC upon the use of the REIC as a general purpose dosimeter. To determine air-kerma read by the REIC dosimeter, one must know the surface charge density $\sigma_i$ residing on the electret at the end of the charging process, and the surface charge density $\sigma_f$ remaining at the beginning of the discharge process: where $(\sigma_f - \sigma_i)$ is proportional to the air-kerma delivered to the REIC. This can be accomplished by making some simple measurements during these processes, and correcting for any charge lost due to natural decay by heat-treatment which is discussed in Chapter 6.

By noting the residual current density present at the end of the charging process $j_{res}$, it is possible to calculate the charge density then present on the electret surface. Since at steady state, the displacement current density term of Eq. (5.33) is zero,
the measured current density \( j = j_{\text{res}} \) will equal the conduction current density through the air, \( j_{\text{sat}} \cdot \tanh \left( \frac{E_a}{R(a j_{\text{sat}})^{1/2}} \right) \). Using this relationship to solve for \( E_a \), one can then solve for the surface charge density using Eq. (5.34).

By noting the time necessary for the discharge of the REIC, selecting for instance the time at which the measured current is half of its initial discharge value, and knowing the dose rate during discharge, one can then fit the solution of Eq. (5.41) to match this time by varying the value of the surface charge density at the beginning of the discharge process. The value \( \Delta \sigma = \sigma_f - \sigma_i \) is the change in surface charge density brought about by the air-kerma received between charging and discharging processes.

5.4.1 Maximum Error

Unfortunately, RIC effects are both \( E_p \) and \( \dot{K} \) dependent, introducing unknown factors into the determination of the air-kerma received. We are, however, able to evaluate the maximum error introduced by RIC.

The air-kerma \( K \) to be measured is expressed as

\[
K = \int_0^T \dot{K} \, dt = \dot{K} T
\]

(5.42)

where \( T \) is the time over which the air-kerma was delivered, and we assume that \( \dot{K} \) is constant for small \( K \). Using Eq. (5.36), we can state that the change in surface charge density \( \Delta \sigma \) caused by \( K \) can be stated as

\[
\Delta \sigma = \int_0^T j_{\text{sat}} \tanh \left( \frac{E_a}{R(a j_{\text{sat}})^{1/2}} \right) - g E_p \, dt
\]

(5.43)

where the sign of \( j_a \) will have changed because \( E_a \) has a negative value during discharge. Here we assume that the REIC was exposed only once to ionizing radiation, so we may assume that \( j_a \) remains constant at the value of \( -j_{\text{sat}} \) throughout the exposure. Similarly, to maximize the calculated error, we will
assume that $E_p$ remains constant at its maximum value, and that the conductivity is also constant and at its maximum, resulting in the following equation:

$$g = g_{\text{max}} \left( \frac{E_p}{E_{p_0}} \right)^{0.3} \left( \frac{\dot{K}}{K_o} \right)^{0.67}.$$  \hspace{1cm} (5.44)

We may now restate Eq. (5.43) as

$$\Delta\sigma = \left[ -j_{\text{sat}} - g_{\text{max}} \left( \frac{E_p}{E_{p_0}} \right)^{0.3} \left( \frac{\dot{K}}{K_o} \right)^{0.67} \right] T.$$  \hspace{1cm} (5.45)

If we solve Eq. (5.45) for $T$, and substitute this expression into Eq. (5.42), we can express the determined air-kerma as a function of air-kerma rate:

$$\dot{K} = \frac{\dot{K}\Delta\sigma}{-\dot{K}\kappa a - g_{\text{max}} \left( \frac{E_p}{E_{p_0}} \right)^{0.3} \left( \frac{\dot{K}}{K_o} \right)^{0.67} \left( \frac{\dot{K}}{K_o} \right)^{0.67} E_p},$$  \hspace{1cm} (5.46)

where $j_{\text{sat}}$ has been expressed as $\dot{K}\kappa a$. A typical calculation of Eq. (5.46) is shown in Fig. 5.5 as the ratio of air-kerma to lost surface charge density. Equation (5.46) states that, for a given reduction in surface charge density, the air-kerma actually delivered to the REIC can range from a minimum value of zero, at the limit of a zero air-kerma rate, to a maximum value of $\Delta\sigma/\kappa a$, at the limit of an infinite air-kerma rate. As an example, consider the REIC charged as shown in Fig. 5.4. The surface charge density at the end of charging has a value of 2.94 nC/cm$^2$, as calculated using Eq. (5.34) for $E_a = 0$. If we suppose that, upon discharge, we find that the change in surface charge density between charging and discharging was $-0.5$ nC/cm$^2$, we can use Eq. (5.46) to calculate that if $\dot{K} >> 1$ mGy/s, the air-kerma would be 35 mGy, while if $\dot{K} = 10^{-6}$ mGy/s, the air-kerma responsible for the same loss of surface charge would be 3 mGy. If the thickness of the polymer is increased ten-fold to 0.25 cm, the minimum air-kerma would be changed to 23 mGy, while the maximum would remain unchanged.
5.4.2 Real Error

It should be noted, however that as the air-kerma rate descends, the time required to deliver a given air-kerma increases and the assumption that $g$ remains constant at the value of $g_{\text{max}}$ may no longer be valid. This can be shown to be true when large air-kermas are administered to the REIC. When Eq. (5.40) is solved for $E_a(t)$, and Eq. (5.35) is used to solve $E_p(t)$
Figure 5.6 Current and charge density through an electret calculated for time of discharge using a high air-kerma rate (0.014 mGy/s).

simultaneously, $j_p(t)$ can be predicted. The results of one such calculation are shown in Fig. 5.6 for a 2.54 x $10^{-3}$ cm thick Teflon (FEP) electret initially charged to 200 V, in a chamber with a 0.4 cm air-gap, and irradiated with 80 mGy at a rate of 0.014 mGy/s. The solid line indicates the current density flowing through the electret as a function of time of irradiation, and the dashed line is the
integrated current or charge density. The current density quickly rises to a value near the maximum as stated by \( g_{\text{max}} \left( \frac{E_0}{E_{\text{req}}} \right)^{0.3} \left( \frac{\mu}{\mu_0} \right)^{0.67} E_p \approx 0.74 \ \text{pC/cm}^2\text{s} \) but then descends rapidly over the following 2000 s, making the total charge loss through the electret 1000 pC/cm² after the air-kerma of 80 mGy. This may be compared with a similar calculation performed for the same electret with an air-kerma rate of 0.55 mGy/s, the results of which are shown in Fig. 5.7. Again the current density rises to the peak expressed by \( g_{\text{max}} \left( \frac{E_0}{E_{\text{req}}} \right)^{0.3} \left( \frac{\mu}{\mu_0} \right)^{0.67} E_p \approx 8.7 \ \text{pC/cm}^2\text{s} \), giving a total charge loss of 800 pC/cm². In both Figs. 5.6 and 5.7, the peak current density is slightly less than predicted since the exponent \( \Delta_1(t) \) had not reached its limit of 0.3 at the time of the peak of \( g_e(t) \). The charge density predicted to be discharged through conduction of ions through the air-gap is 1.1 nC, thus the discrepancy of total charge loss due to RIC is \( (1100 - 800)/(1100+1100) \) or 14% due to the change in air-kerma rate form 0.014 mGy/s to 0.55 mGy/s. The relative proportion of peak electret current density to current flowing through the air is much greater in the former case, but because of the necessary duration of the irradiation, \( j_p \) is very small for most of it. The result is that the loss through the electret is very similar in the case of both the high and low air-kerma rates.

The change in surface potential \( \Delta \sigma \) can be solved for with Eq. (5.46), and the result substituted into Eq. (5.34) setting \( E_0 = 0 \) to find the change in potential as a function of air-kerma. For a 2.54 \times 10^{-3} \text{ cm thick Teflon (FEP) electret initially charged to 200 V, in a chamber with a 4 mm air-gap, and irradiated with 80 mGy at a rate of 0.014 Gy/s, a 72.7 V drop is predicted, while for the same chamber irradiated at 0.55 mGy/s, a drop of only 32.4 V is predicted though the same air-kerma of 80 mGy is administered.

It is predicted, however, by the more accurate Eq. (5.40) applied to the set-up discussed above, that, for a dose of 80 mGy administered at a rate of 0.55 mGy/s, there will be a loss of 19.6 V, while if the same REIC is exposed to 80 mGy at
Figure 5.7 *Current and charge density through an electret calculated for time of discharge using a low air-kerma rate (0.55 mGy/s).*

a rate of 0.014 mGy/s there will be a loss of 20.2 V. These values are very close and, under our current set-up, are not resolvable experimentally.

Figure 5.8 shows the approximate calculations from Eq. (5.46) and the more accurate results from the full simulation, using Eq. (5.40), of air-kerma required to bring about (a) a 30 V and (b) a 2.8 V drop in surface potential. Similarly
Fig 5.9 shows the approximate and more accurate calculations of loss of surface potential brought about by (a) a 1 mGy air-kerma and (b) an 80 mGy air-kerma.

The calculated effects of RIC can be seen in Figs. 5.10 and 5.11, in which the interpreted dosimeter reading has been calculated as a function of air-kerma rate for different initial surface potentials, air-kermas, air-gaps, and electret thicknesses. The base configuration common to the four graphs is a 400 V initial potential, 0.4 cm air-gap, 1.0 mGy and $2.54 \times 10^{-3}$ cm electret. From this configuration the parameters are varied to produce the curves shown.

The value of expected reading can be obtained from the calculated loss of surface potential by the expression

$$
\Delta K = \frac{\Delta V \varepsilon_o (p + \varepsilon_p a)}{\kappa a^2 p},
$$

which follows from Eq. (5.34) and the relationship between a change in surface charge density, $\Delta \sigma$ and a small air-kerma $\Delta K$ when RIC is assumed to be negligible:

$$
\Delta \sigma = \Delta K \kappa a.
$$

The reading is true for an air-kerma rate above 1 mGy/s in most configurations, although as the total air-kerma is increased, the threshold rate for giving true readings is pushed up. This can be seen in Fig. 5.10 (b), in which insensitivity to air-kerma rate can be found above 0.1 mGy/s for an air-kerma of 0.1 mGy but above 10 mGy/s for an air-kerma of 10 mGy.

The falling off of the reading above a certain rate, e.g. 1000 mGy/s in Fig. 5.10 (b) can be attributed to a lack of saturation conditions above this point, i.e., ion generation occurs too rapidly for the ions to be collected before recombining. To eliminate this problem, which is not related to RIC, the surface potential of the electret would have to be increased as is shown in Fig. 5.10 (a). Here, for an initial potential of 1000 V, there is no loss of saturation conditions for the range of air-kerma rates shown.
Figure 5.8 Calculations of air-kerma required to cause (a) a 30 V drop in charge and (b) a 2.8 V drop in surface potential, for a 0.00254 cm Teflon (FEP) electret charged to 200 V in a 0.4 cm air-gap chamber.
Figure 5.9 Calculations of change in surface potential caused by (a) an air-kerma of 1 mGy and (b) an air-kerma of 80 mGy, for a 0.00254 cm Teflon (FEP) electret charged to 200 V in a 0.4 cm air-gap chamber.
Figure 5.10 The simulated reading of an REIC as a function of air-kerma rate for (a) a 0.4 cm air-gap, irradiation to 1.0 mGy, and a 0.00254 cm electret for varying initial surface potentials; and (b) a 0.4 cm air-gap, 400 V initial surface potential, and 0.00254 cm electret for irradiation to different air-kermas.
Figure 5.11 The simulated reading of an REIC as a function of air-kerma rate for (a) a 400 V initial surface potential, irradiation to 1.0 mGy, and a 0.00254 cm electret for varying air-gaps; and (b) a 0.4 cm air-gap, 400 V initial surface potential, and irradiation to 1.0 mGy for varying electret thicknesses.
From Fig. 5.10 and 5.11, it can be seen that to reduce the effects of RIC on the operation of the REIC, it is necessary to maximize both the air-gap thickness and the electret thickness, and to minimize the initial surface potential. There is, however, a limit that applies to these values brought about by the needs to keep the electric field strength sufficiently high to minimize problems due to a loss of saturation, keep a sufficiently large guard-ring to maintain linear response over the entire theoretical range of the REIC, and to have the device small enough to be conveniently worn by personnel.

5.5 Detection of RIC Effects

A good experimental method for the detection of the effects of RIC was to expose a chamber several times to the same air-kerma but delivered at different rates which were chosen to lie on the steepest part of the 10 mGy curve shown in Fig. 5.10 (b). This configuration was chosen because it would offer an easily detected discrepancy between changes in surface potential. If RIC effects were significant, the voltage drop in the two chambers would be measurably different. The time required for the delivery of an air-kerma of 10 mGy to the first chamber at a rate of 0.005 mGy/s was 2000 s or 33.3 min. This is a rather long time, over which a significant amount of natural or dark decay can occur. To prevent natural decay, the electret was heat treated after charging by holding it at a temperature of 95 °C for 10 minutes, a discussion of which can be found in Chapter 6. The second exposure was at a rate of 0.6 mGy/s, requiring 0.28 minutes, and the final exposure was at a rate of 16 mGy/s requiring 0.01 minutes. Charging potential was 1000 V, but the surface potential remaining after heat treatment was 450 V. The chamber had an air-gap of 0.4 cm, and the electret was $2.54 \times 10^{-3}$ cm thick.

The results of our experiment are shown in Fig. 5.12 and clearly demonstrate a dependence of dosimetric response on air-kerma rate for the particular chamber.
configuration discussed. The error due to this dependence can be seen in Fig. 5.10 (b) to be roughly equal to 40 mGy.

Our work indicates that, for relatively large air-kermas, as 10 mGy can surely be considered in the context of personnel dosimetry, there is less dependence on air-kerma rate than is suggested by Eq. (5.46), though the dependence predicted by Eq. (5.40) and observed experimentally represents a possible discrepancy of approximately 400 % which is equal to 40 mGy in this instance. Nevertheless, it seems that through a proper choice of electret thickness, initial potential and air-gap width, the dependence on air-kerma rate can be reduced to a level giving an acceptable dosimetric error of below 20 %.
Figure 5.12 *Comparison of calculated to measured values for loss of surface potential as a function of air-kerma rate. Error shown on the experimental points is due solely to the error in the measurement of the surface potential. Initial surface potential was 400 V, $a = 0.4 \text{ cm}$, $p = 2.54 \times 10^{-3} \text{ cm}$, $K = 10 \text{ mGy}.$*
References


# Chapter 6

## Decay

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6.1 Introduction

In this chapter, decay measurements of radiation-charged electrets, are presented and compared to similar measurements of corona-charged electrets. The decay characteristics were obtained through ageing the electrets at room temperature. In addition, the short-term decay characteristics are investigated and characterized, and heat-treatment is shown to be able to prolong the life of radiation-charged electrets.

6.2 Long-term Decay

To characterize the long-term decay of untreated, radiation-charged electrets, several were charged, then placed in a well sealed bowl, at a relative humidity of approximately 20 % using desiccating salts. Two of the electrets were exposed to high temperature (95 °C) for 30 minutes before charging. From time to time the electrets were removed from the bowl and the surface potential measured with the electrostatic probe. The electrets were then returned to their storage conditions.

The surface-potential information from each electret was averaged over a small area located at the centre of the electret and over a short period of time roughly equal to 2 seconds to produce each reading. These averages are displayed in Figure 6.1 (a) as normalized functions of time. All Teflon (FEP) electrets (clean, uncleaned, 25 μm thick, 75 μm thick, heat-treated and untreated) exhibit decay characteristics that can be described by two periods of decay. The first period of decay lasts from 15 to 20 days, after which the electret charge rests at roughly 85 % of its original value. The extended time decay may indicate the large value of the bulk resistivity, \( r_B \), with a decay time constant of \( r_B \varepsilon \varepsilon_0 \) where \( \varepsilon \) and \( \varepsilon_0 \) is the relative dielectric constant and the vacuum permittivity, respectively. Following the rapid decay, a second period of slow decay begins. The second decay is non-linear, but over the period of our observations a straight line can be appropriately
Figure 6.1 Normalized decay patterns of various electrets that were charged and stored in low humidity conditions.

Fitted to the data. Loss measurements for a Mylar (PET) electret are also shown and it is clear that Teflon (FEP) is better suited for long term charge storage, perhaps owing to the hydrophobic nature of Teflon (FEP) which would greatly reduce external losses. The 75 μm Teflon (FEP) electret had been monitored for 195 days, and at that time possessed 80% of its original charge. The thicker Teflon (FEP) electret was also not subjected to heat treatment, and it appears that the deceleration of loss expected due to the weaker electric field across the polymer is offset by the lack of heat treatment which decreases loss by deepening
the average trap depth. The effect of cleaning with acetone and lens tissue seems to be negligible as the decay curve of the uncleaned electret follows almost exactly that of the cleaned electret. It is merely shifted down by about 2% during the linear decay portion. The cleaned electret (25 µm Teflon (FEP)) was at 83.64% after 117 days, and a similar but uncleaned electret was at 82.43% of the original charge, respectively. Both of these samples decay with a rate of approximately 0.03% per day as well, once the quasi-constant decay rate is achieved. Mylar (PET) (p = 0.11 mm) suffers from more rapid decay, falling to 56% of its original charge after only 68 days, possibly owing to the shallower trap depth of Mylar (PET) (with an equivalent activation energy $\epsilon_x$ of 0.18 eV) compared with Teflon (FEP) ($\epsilon_x$ = 0.5 eV). Also, the schubweg, which is the mean distance travelled by a charge carrier before recombination, of carriers in Teflon (FEP) is on the order of a factor of 6 less than in Mylar (PET). The measured decay for Mylar (PET) appear to correspond very well to the internal decay of charge from corona-charged Mylar (PET)$^2$ which would restrict its use in REIC’s.

In Chapter 4, we discussed the change in surface-charge distribution during the actual radiation-charging and -discharging process of the electret. In this chapter, however, we also measured the distribution of charge during the decay period once the electret has been charged. Figure 6.2 shows a series of charge profiles (surface potential as a function of radius) measured over an electret at various points in its decay history. The electret studied here is the 25 µm Teflon (FEP) which showed very little fluctuation in distribution over time. It can be seen from this set of curves that the little change in distribution which did occur, only occurred at the edge of the electret surface, leaving largely unaffected the practical distribution. Certain measurements in the decay of corona-charged polyethylene electrets$^3$ exhibit charge-distribution-uniformity that are similar to ours, while others$^4$-$^5$ exhibit greater distortions in charge distribution.
Radiation-charging is expected to produce electrets with charge retention properties very similar to those produced by corona charging because of the similarities between the two charging methods. In each, air ions of low energy impinge on the surface of the electret. We applied a decay model proposed by von Seggern\(^6\) that describes the decay of charge from the surface and bulk of a corona-charged insulating material and assumes that decay is due solely to the injection of surface-charges into the insulator bulk through which they migrate to the backing grounded electrode or, in which they recombine with thermally generated carriers. The model is based on the piece-wise solution of three simultaneous differential
where $\mu_Q$ is the shallow-trap-modulated mobility, $\rho_Q$ is the quasi-free charge density, $\tau_Q$ is the characteristic time constant describing the period during which the quasi-free carriers remain in the quasi-conduction energy band before being trapped, $\rho_T$ is the deep-trapped charge density, and $\tau_T$ is the time constant describing the period during which carriers are deeply-trapped before being excited into the conduction band. $E$, $x$, and $t$ represent electric field strength, distance and time, respectively. Our boundary conditions are: $E(0, t) = (\sigma_s/\varepsilon\varepsilon_o)e^{-t/\tau_o}$, $E(x, 0) = \sigma_s/\varepsilon\varepsilon_o$, $\rho_Q(x, 0) = 0$, $\rho_T(x, 0) = 0$ where $\sigma_s$ is the initial surface charge density and $\tau_o$ is the time constant describing surface charge injection. The set of equations requires knowledge of four parameters: $\mu$, the mobility of free charge carriers; $\tau_o$, the time constant determining decay of surface charge; $\tau_Q$, the rate constant for quasi-free charge carriers leaving the quasi-conduction band; and $\tau_T$, the rate constant for escape of deeply trapped charge carriers. These parameters were measured by von Seggern in Teflon (FEP-A) (polyfluoroethylene propylene) at a temperature of 145 °C. Unfortunately, their values at the temperature (20 °C) at which our experiments were performed, and for Teflon (FEP), the material we studied, are not known. Different experimental methods exist for their determination, and these will be pursued in the near future. We have been able to fit the solution of von Seggern’s model to our data through appropriate choice of the parameters involved. Figure 6.3 compares our data for the 25 μm, heat-treated and cleaned Teflon (FEP) electret with the solution of the decay model, for which the equations governing the decay:

$$
\mu_Q \rho_Q(x, t) E(x, t) + \varepsilon\varepsilon_o \frac{\partial E(x, t)}{\partial t} = 0 \tag{6.49}
$$

$$
\frac{\partial \rho_T(x, t)}{\partial t} = \frac{\rho_Q(x, t)}{\tau_Q} - \frac{\rho_T(x, t)}{\tau_T} \tag{6.50}
$$

$$
\varepsilon\varepsilon_o \frac{\partial E(x, t)}{\partial x} = \rho_Q(x, t) + \rho_T(x, t) \tag{6.51}
$$
parametric values displayed in Table 6.1 were used. As would be expected, a lower mobility and greater time constants than those utilized by von Seggern were obtained for our case at the reduced temperature. The decay of intrinsic charge carrier density, induced by the radiation used to charge the electret, is not accounted for in this model, and is likely to be reflected in the values that we used for the parameters used to fit the model to the data.

Thermally stimulated discharge (TSD) techniques have not as yet been used to evaluate the charge-storage and charge-decay processes of the radiation-charged electrets, but are presently being implemented in our laboratory. However, simple decay characteristics verified through natural ageing of the electrets does provide an important preliminary indication of charge decay. In conclusion, results of decay measurements through ageing from radiation-charged electrets were presented and compared to those from corona-charged electrets and found to be quite similar. We also briefly considered the fitting of the decay data to a model describing the decay of corona charged electrets. Decay from radiation-charged Teflon (FEP) electrets was found to be characterized by approximately a one week period of rapid decay, followed by a long period of quasi-stable decay rate.
Figure 6.3 Fit of modelled charge decay to measured data.

Table 6.1 Parameters used in modelling charge decay.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Radio-charged electrets $T=20^\circ$C</th>
<th>Corona-charged electrets $T=145^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ (m$^3$/Ns)</td>
<td>$1.6 \times 10^{-19}$</td>
<td>$1.6 \times 10^{-16}$</td>
</tr>
<tr>
<td>$\tau_Q$ (s)</td>
<td>720 000</td>
<td>5760</td>
</tr>
<tr>
<td>$\tau_T$ (s)</td>
<td>$4.8 \times 10^6$</td>
<td>38 400</td>
</tr>
<tr>
<td>$\tau_0$ (s)</td>
<td>97 500</td>
<td>780</td>
</tr>
</tbody>
</table>
6.3 Short-term Decay

The decay over short periods of time following charging was measured in a similar fashion to the decay over long periods, with the exception being that the charged electrets were not stored in a desiccating bowl between measurements, owing to the brevity of these intervals, which were roughly 30 minutes in duration. It was felt that opening the bowl every thirty minutes would reduce the effectiveness of the desiccating salts to near zero.

Five electrets were charged in five separate but identical chambers. Measurements were taken over a period of at least 300 min after charging, and the results of the decay measurements are shown in Fig. 6.4, with the curves grouped according to trial number. The decay pattern is similar to those seen over the long term, with a rapid exponential decay followed by a slow linear decay, but is much more severe when considered on the same time scale. It is possible that opening the chamber more often for measurement and the lack of control over the humidity of the environment has an adverse affect on the storage of charge.

The value of the surface potential at the 300 minute mark, interpolated if necessary, is shown in Table 6.2. The potential remaining after 300 min of decay time seems to rise with each successive charging, while the standard deviation over the five chambers remains high, indicating that each electret possesses its own decay characteristics.
Figure 6.4 Short-term decay measurements, grouped according to trial number.
Table 6.2 *Average surface potential at the 300 minute mark for each trial. Averaged over all electrets.*

<table>
<thead>
<tr>
<th>Trial</th>
<th>Surface Potential at $t = 300$ min (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>167 ± 12.2</td>
</tr>
<tr>
<td>2</td>
<td>170 ± 10.2</td>
</tr>
<tr>
<td>3</td>
<td>172 ± 18.0</td>
</tr>
</tbody>
</table>

While the chamber to chamber variation is high, each chamber behaves relatively consistently. The decay curves are shown in Fig. 6.5 grouped according to chamber, and the value of the surface potential at the 300 min mark is shown in Table 6.3. Here the average error is 6.9 V. An interesting characteristic of the short-term decay is that, while the initial rapid decay varies from electret to electret, the decay following the 100 min mark is easily fitted to a straight line, and the slope of this line is fairly constant from one electret to another.

The slopes of the curves shown in Fig. 6.5 (c) are evaluated from the 100 min to the 300 min mark and are listed in Table 6.4. The average of these values is $-0.027$ V/min with an error of ± 0.013 V/min. If the surface potential of the electret is measured at the 100 min mark, the value at the 300 min mark can be predicted with a precision of 2.2 V, considerably less than the minimum of 6.9 V predicted above.

6.4 Heat Treatment

It has been shown by various authors that exposure of the electret to elevated temperatures for extended periods after charging can significantly enhance the life-
Figure 6.5 *Short-term charge decay measurements grouped according to electret number. Number of trials per electret vary.*
Table 6.3 Average surface potential at the 300 minute mark for the different chambers. Averaged over trial number.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Surface Potential at $t = 300$ min. (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>178 ± 5.8</td>
</tr>
<tr>
<td>2</td>
<td>151 ± 1.0</td>
</tr>
<tr>
<td>3</td>
<td>172 ± 4.4</td>
</tr>
<tr>
<td>4</td>
<td>175 ± 13.6</td>
</tr>
<tr>
<td>5</td>
<td>178 ± 9.5</td>
</tr>
</tbody>
</table>

time of the electret\textsuperscript{9,10}. It has been postulated that heat treatment can restore the dielectric to its pre-irradiated state by allowing the electron-hole pairs generated by radiation to recombine and reducing the conductivity of the electret to its intrinsic value. Heat treatment has also been proven to be beneficial with regard to charge retention even when radiation is not used in the charging procedure. Temperatures ranging from 60 °C to 200 °C applied over periods of a few seconds to an hour are useful heat-treatment conditions for Teflon (FEP) electrets, because the major energy levels for trapping sites lie between 90 °C and 220 °C\textsuperscript{9,10}. The benefits from heat treatment, then seem to derive from a combination of the elimination of delayed radiation induced conductivity and the emptying of energetically shallow traps.

In a study of the impact of heat treatment on the life-time of radiation charged electrets, we charged $2.54 \times 10^{-2}$ cm thick and $2.54 \times 10^{-3}$ cm thick electrets to potentials of 200 V and 1000 V, respectively. The former electret was then
Table 6.4  *Slope of straight-line fitted to points from 100 minutes to 300 minutes, with standard error of fit.*

<table>
<thead>
<tr>
<th>Trial</th>
<th>Slope (V/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.030 ± 0.008</td>
</tr>
<tr>
<td>2</td>
<td>-0.045 ± 0.010</td>
</tr>
<tr>
<td>3</td>
<td>-0.029 ± 0.010</td>
</tr>
<tr>
<td>4</td>
<td>-0.016 ± 0.006</td>
</tr>
<tr>
<td>5</td>
<td>-0.026 ± 0.005</td>
</tr>
<tr>
<td>6</td>
<td>-0.013 ± 0.005</td>
</tr>
</tbody>
</table>

subjected to a temperature of 95 °C for a period of 10 minutes, stored in dry conditions for long-term monitoring and atmospheric conditions for short-term monitoring, and was dismantled periodically so that its surface potential could be measured using the electrostatic voltmeter probe. The latter electret was treated similarly, with the exception that the heat treatment was performed three times: once upon charging, once after two days of storage, and once again on the second day, after a short irradiation of 10 mGy. Temperatures higher than 110 °C could not be applied in our experiments because of the low melting points of the chamber walls, but despite these limitations, we were able to demonstrate that heat-treatment can improve the life-times of radiation charged electrets. This improvement could probably be further enhanced by the use of higher temperatures and a temperature resistant plastic for the wall material.
It was found that the decay rate of surface potential was greatly reduced by exposure to a high temperature. The surface potential history of a $2.54 \times 10^{-3}$ cm Teflon electret, initially charged to 1000 V in a chamber having a 0.4 cm air-gap, and the history of a $2.54 \times 10^{-2}$ cm electret charged to 200 V in a similar chamber are shown in Fig. 6.6. For the thinner electret, heat-treatment takes place immediately after charging, two days after charging and again on the second day, after a low air-kerma exposure of 10 mGy for a total heat treatment time of 30 minutes. For the thicker electret, heat-treatment is applied only once, immediately after charging. Though decay is dramatically slowed by the single heat-treatment given to the thicker electret, which also had the lower initial potential, it is seemingly eliminated by the repeated heat-treatment applied to the thinner electret with the higher potential. It should be remembered from Chapter 2 that when the thickness of an electret is reduced, the charge density needed to produce a given potential rises. So not only was the electric field increased by making the electret thinner and raising the initial potential, but the density of trapped charge carriers was raised by a factor of 50. Despite this, the thinner electret displayed better charge retention characteristics than the thicker one, losing less of its original charge to heat treatment, and losing charge at an undetectable rate thereafter.
Figure 6.6 Charge histories of two electrets, both subjected to heat treatment.
References


Chapter 7
Characteristics of the Radiation-Charged Electret Dosimeter

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7.1 Introduction

As has been discussed in previous chapters and as demonstrated by others,\(^1\)\(^-\)\(^4\),
electret ionization chambers can serve as integrating radiation dosimeters. In this
chapter we discuss the feasibility of using the radiation charged electret ionization
chamber (REIC) for personnel dosimetry. Radiation charging prepares the REIC
which is subsequently used in the working environment, with the surface charge
decreasing due to the air kerma received. The amount of remaining charge can then
be determined either by radiation discharging and measurement of the integrated
current with an electrometer if RIC is accounted for in the discharge process, or
by direct measurement of the surface potential using an electrostatic voltmeter
probe, as mentioned in Chapter 3. The difference in electret surface charge before
and after the use of the dosimeter is related to the air kerma received during the
monitoring task. The life cycle of the dosimeter entails its charging, its use in
the field, its discharging for reading purposes and its recharging \textit{in situ}. If the
discharge reading method is used, all of this can occur without dismantling the
dosimeter as is required of electret dosimeters relying on other electret forming
techniques. The method chosen for reading the charge information on the electret
after exposure must be carefully considered.

The properties of our dosimeter that must also be examined include sensitivity
or minimum detectable dose, maximum detectable dose, linearity, natural decay,
rate response, energy response and directional dependence. The directional depen­
dence is largely a function of chamber materials, shape and quality of radiation,
and was not considered in this work. Dependence on some of the parameters just
mentioned (e.g., linearity), were determined by direct radiation discharge, while
another (i.e., electret decay) was determined with a non-contact probe, as shown
in Chapter 6; the measurement technique used to determine the effect of each
parameter is specified in the appropriate following sections.
7.2 Results and Discussion

7.2.1 Sensitivity

As in any ionization chamber, the response of the proposed dosimeter to radiation can be altered by varying the size of the sensitive volume, i.e., by changing the size of the air gap. If measurement of the charge is performed via discharge, then the sensitivity will also depend on the area of the collecting electrode. If the electret dosimeter is kept under saturation conditions during its monitoring task, and no charge is lost due to decay, the change in surface charge density due to an air kerma, $K_{\text{air}}$ is

$$\Delta \sigma(K_{\text{air}}) = \sigma_o - \sigma_f,$$  \hspace{1cm} (7.52)

where $\sigma_o$ is the initial electret charge density, $\sigma_f$ is the charge density remaining after irradiation.

The ideal response of the REIC, as for ionization chambers in general, can be stated as

$$j = K\kappa a,$$ \hspace{1cm} (7.53)

where $\kappa$ and $a$ are defined in Section 5.3.

If we integrate Eq. (7.53) over a period of time, we can state that

$$\Delta \sigma = K\kappa a.$$ \hspace{1cm} (7.54)

If we choose to read the chamber via discharge, then we must also integrate over the area of the collecting electrode to know the difference between the total charge deposited in charging $q_i$ and the total remaining charge removed during discharge, $q_f$

$$\Delta q = q_i - q_f = K\kappa a A,$$ \hspace{1cm} (7.55)
where \( A \) is the area of the collector. With commercially available ion chambers, it is sometimes difficult to determine with sufficient accuracy what the critical dimensions of the chamber are, making Eq. (7.55) insufficiently accurate for the determination of air-kerma, which can cause a small error. To eliminate the effects of these inaccuracies, a dimensionless calibration constant \( \kappa' \) is determined experimentally by comparing the chamber response to a standard, and then multiplied on the right-hand side of Eq. (7.53). For the purposes of this thesis, we will assume it carries a value of 1, and therefore ignore it. Now the minimum detectable dose can be determined by substituting the uncertainty in our measurement of \( \Delta q \). This uncertainty is determined by the electrometer, the degree to which the cables to the REIC are successfully shielded from radiation, and the degree to which RIC is understood and accounted for. The uncertainty inherent to the electrometer is usually very small and can be overcome by the use of a collector electrode which is sufficiently large for the signal-to-noise ratio to be as high as desired. A large collector, however, requires a large guard-ring to ensure linear response over an appreciable range.

The uncertainty due to chamber “leakage” arises from poorly shielded cables and collector surfaces. It is more difficult to deal with, but can be minimized if strict attention is paid to: collimation of the radiation beam so that an area only as large as the collector and guard-ring is irradiated during reading, and use of a co-axial cable in which the center wire is connected directly to the collector and the outer braid is connected to the guard-ring.

Figure 7.1 illustrates the results of an experiment designed to evaluate the minimum detectable dose for discharge measurement. The parameters of the chamber were: external potential \( V_0 = 100 \) V, collector radius of 2.4 cm, guard-ring thickness of 0.1 cm, and an air gap of 0.4 cm. A Siemens Polydoros 80 fluoroscopy unit was used to deliver a known dose to the REIC. Ten trials were
\[ \Delta q = (0.429 \text{ nC/nGy})K \]
\[ r = 0.9987 \]

**Figure 7.1** Typical reproducibility of an electret chamber subjected to ten independent trials, with the error bars representing the standard deviation. The parameters of the chamber were: an external potential of 100 V, a collector radius of 2.4 cm, a guard thickness of 0.1 cm, an air-kerma rate of 1 mGy/s and an air gap of 0.4 cm.

performed. Average charge removed is shown as a function of the air-kerma, with the error-bars representing the standard deviation of the measured charges. With the configuration used here, a minimum detectable dose of 0.08 mGy was achievable.
A different analysis applies to measurement of the surface potential with the electrostatic voltmeter probe. When the REIC is assembled, and there is no external potential applied, the electric field in the air-gap can be written as

$$E_a = -\frac{p\sigma}{\varepsilon_0(p + a\varepsilon_p)}.$$  \hfill (7.56)

If $\Delta \sigma$ from Eq. (7.54) is substituted into this expression, we can describe the noise in our voltage measurement system as

$$\Delta V = \Delta E_a a = -\frac{p\Delta K \kappa a^2}{\varepsilon_0(p + \varepsilon_p a)}. \hfill (7.57)$$

According to Eq. (7.57), for an REIC of air-gap equal to 1.0 cm, electret thickness equal to 0.25 cm, and a noise value of 4 V, the minimum detectable air-kerma, is roughly 0.02 mGy. The errors inherent in either measurement technique are very similar to the best numbers reported for TLDs $^5,^6$. A probe-to-surface distance of less than 2 mm would reduce the noise on the signal from the probe, as was shown in Chapter 3.

### 7.2.2 Range and Linearity

The range and linearity of the REIC are intimately connected, because the range is defined as the total air-kerma over which the response is linear. The range can be nominally determined from Eq. (7.57) by substituting the initial electret surface potential for $\Delta V$, and calculating $\Delta K$. Linearity is impaired before this value is reached, however, by two factors: the loss of saturation conditions, i.e., the recombination distance is shorter than the air-gap thickness, and the warping of electric field lines that effects the space from which the collector draws. The latter phenomenon was described in Chapter 4 in which the evolution of electric field lines was predicted numerically. This problem can be largely circumvented by using the electrostatic probe measurement technique by which the potential at the center of the electret is measured. The center is the last region to be affected by
the changes in direction of electric field lines. This can also be accomplished with
the discharge measurement technique, by making the collector electrode very small
with respect to the guard-ring, but in this case the measured signal is proportionally
smaller, reducing the sensitivity.

Figure 7.2 (a) shows the dependence of surface charge density on air-kerma
received by the dosimeter, and how the range depends on the initial potential of
the electret. The configuration of the chamber used in this experiment was as
follows: \(a = 0.2\) cm, \(p = 0.011\) cm of Mylar (PET) with \(\varepsilon_p = 3.2\), the collector
radius \(c = 19\) mm, and the guard-ring width \(g = 5\) mm. It is clear that a very
large linear range is attainable by increasing the initial potential of the electret.
The limit placed on the surface potential arises from the break-down strength
of the air, 3 kV/mm, the maximum attainable density of trapped charge carriers
on the surface of the dielectric, and the error brought on by radiation induced
conductivity in the electret, as discussed in Chapter 5. It is generally the latter
that poses the more serious problem, and in order to keep the error due to radiation
induced conductivity to a reasonably low value of 10 % it is necessary to restrict
the magnitude of the electric field in the electret. This limits the range of the
dosimeter, but should still permit a design offering a range that greatly exceeds
the maximum permissable effective dose to a radiation worker.

7.2.3 Charge Decay

The effect of charge decay on the operation of the REIC as a dosimeter, can
be greatly reduced by heat-treatment of the electret after charging. Heat treatment
empties the energetically shallower traps in the electret, so that those excess charges
that remain trapped are quite stable. It also reduces the delayed radiation induced
conductivity of the electret, by allowing electron-hole pairs created in the electret
by radiation to recombine, thus returning the electret to its pre-radiation conditions.
For the proper choice of wall materials, the ideal temperature and duration for heat-
Figure 7.2 (a) General dosimeter response for various geometries and $V_0$. Charge density removed versus air-kerma for a constant air-gap and various initial charging voltages. (b) Response to air-kerma shown at a smaller scale.
treatment will probably be near 200 °C and one hour, respectively. However, even the relatively low temperature of 95 °C to which we were able to subject our REIC was able to cause a marked improvement in the decay of the electret charge, as was shown in Chapter 6.

7.2.4 Rate Response

Radiation induced conductivity in the bulk of the electret renders the response of the REIC to air-kerma sensitive to the rate at which the air-kerma is delivered. The tendency of the REIC to be sensitive to air-kerma rate can be dealt with by ensuring that the electric-field strength in the polymer is as low as possible, and that the air-gap is as large as possible. The first measure will reduce the absolute current density flowing through the electret. The second measure will reduce the relative current density in comparison with that flowing through the air-gap, but will also cause an increase in error at the high end of the rate scale by reducing the efficiency with which the REIC collects ions generated in the air-gap. That is, the strength of the electric-field in the air-gap will be less than is needed to prevent the ions from recombining. This being said, the reader should also be reminded that the sensitivity of the REIC depends largely on the size of the air-gap and polymer. It seems that the best way to control error due to radiation induced conductivity is by increasing the thickness of the polymer, the air-gap and the electric-field. A solution of Eq. (5.15) with $a = 1.0$ cm, $p = 0.5$ cm, and $V_0 = 1000$ V, is shown in Fig. 7.3. This curve suggests that, under these conditions, there is a possible error of 0.01 mGy on an air-kerma of 0.1 mGy over a range starting below $10^{-7}$ mGy/s and ending near 300 mGy/s. Depending on the environment in which the wearer of the REIC works, this range should be adequate for the exposures to which he or she could be subjected. As was mentioned above, the range can be extended by increasing the initial potential, but at a cost to the error in the low air-kerma rate region, due to RIC. For example, if the initial potential used to obtain Fig. 7.3 is
Figure 7.3 Response of an REIC with $a = 1.0\, \text{cm}$, $p = 0.5\, \text{cm}$, and $V_o = 1000\, \text{V}$ as a function of air-kerma rate.

doubled to 2000 V, the range of the REIC is extended to 600 mGy/s, while the error due to RIC is increased to 12.6%.

7.2.5 Energy Dependence

Energy dependence is for the most part a function of the materials of which the chamber is constructed, and therefore will change with changes in choice of these materials. We offer an example, however, in which we have verified the overall energy dependence of an REIC with the appropriate ionization chamber at the particular energy in collaboration with a fellow student (L. Ryner)\textsuperscript{7}. The chamber was constructed of fiberglass, rather than polystyrene, the polarizing electrode was made of aluminum rather than graphite, and the electret was of Mylar (PET)
rather than Teflon (FEP). The REIC was initially charged, and the measurements of the remaining electret charge were performed in the radiation discharge mode (i.e., no external potential applied) through the electrometer, and then compared to measurements from standard ionization chambers for that particular photon energy. The results are shown in Fig. 7.4. One notes the attenuation effects at very low photon energies and the over response of the dosimeter at the mid-energy range of 30 to 100 keV due mainly to the photoelectrons emitted from the polarizing electrode. Replacing the aluminium polarizing electrode with a lower atomic number material (e.g. carbon in the form of graphite) may flatten out the peak response at the intermediate energies. Nonetheless, the results can be considered acceptable when compared with the energy response of TLDs\textsuperscript{8} and filtered film badges\textsuperscript{9}. We expect a similar, if not improved response for chambers made of polystyrene.
Figure 7.4 Measurement of energy dependence for REIC with 1.5 mm fiberglass walls, an aluminum polarizing electrode and 0.01 cm Mylar electret.
7.2.6 Summary

There exist many factors which affect the functioning of the REIC as a personnel dosimeter. In this thesis we have investigated just a few: the evolution of the electric-field in the REIC as affected by dimensions of the REIC, the natural decay of charge from the electret surface, and the conductivity of the electret as affected by radiation and the intensity of the radiation. This, combined with our past work on the REIC, enables us to design a useful radiation dosimeter that has a versatile range, low minimum detectable air-kerma and that is not prone to excessive error from unpredictable charge decay, air-kerma rates or radiation energies. Two techniques for reading the charge information on the electret have been discussed: using the electrostatic voltmeter probe or full discharge. They offer comparable sensitivities and ranges. Table 7.1 provides a point-by-point comparison of the advantages and disadvantages inherent to either technique.
Table 7.1 *Comparison of advantages and disadvantages inherent to two methods of extraction of charge information.*

<table>
<thead>
<tr>
<th></th>
<th><strong>Probe</strong></th>
<th><strong>Discharge</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages:</strong></td>
<td>1. Easy construction of chamber. No need for guard-ring or shielded cables</td>
<td>1. No need to disassemble chamber once built</td>
</tr>
<tr>
<td></td>
<td>2. No loss of information resulting from reading</td>
<td>2. Easily performed in hospitals and other settings where access to X-rays is easy</td>
</tr>
<tr>
<td></td>
<td>3. Easy to know initial charge on electret before use of REIC</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages:</strong></td>
<td>1. Necessary to purchase probe.</td>
<td>1. More difficult to measure loss of charge if heat treatment is used - makes it difficult to know initial charge</td>
</tr>
<tr>
<td></td>
<td>2. Disassembly of REIC required - could result in spoiling information by accidental touching of electret</td>
<td>2. Reading electret causes loss of information</td>
</tr>
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References


Chapter 8

Conclusion
We have numerically modeled the evolution of surface charge distributions on the electret in the REIC as it is charged and discharged, with the results agreeing well with measured values for air-gaps of 0.2 cm and 0.8 cm, and an electret radius of 2.5 cm. The electric field is determined by numerical solution of Laplace’s and Gauss’s Equations. The electric-field information is then used in conjunction with an approximation of ion density in the chamber volume to estimate where on the electret charge is deposited. The calculated radial charge distributions are then convolved with a Gaussian function that matches the line-spread function of our measurement system.

Charge distributions were measured with an electrostatic voltmeter probe and a motorized platform used to scan the electret beneath the probe. The distributions were transformed to a cylindrical coordinate system using a simple computer program that gives, as output, radial charge distributions. Such measurements were performed at various times during the charging and discharging of the REIC, and the results agree with the distributions predicted by our model. In obtaining our measurements, we found that the electret charge distribution is sensitive to the presence of strong sources of scatter such as wires used to contact the electrodes.

The success of the model does not appear to be sensitive to the accuracy of the ion-density assumed in the ion chamber, i.e., both an isotropic, one-over-radial-distance-squared distribution, and a directionally dependent approximation of the true distribution produce acceptable results. From information about the evolution of the electric-field, one can make design decisions about guard-ring thickness, the dosimetric range of the REIC, and whether to use probing or discharging techniques for reading charge information recorded on the electret.

We have been able to theoretically account for the effects of radiation induced conductivity on the REIC, with experimental verification of the theoretical results. We have shown that the effects of radiation induced conductivity are not reflected
in the value of the saturation current measured during the charging or discharging processes. Rather, this conductivity serves merely to prolong the charging process and shorten the discharging, and to permit the flow of a residual current at the end of the charging process.

Radiation induced conductivity in dielectrics is dependent on the air-kerma rate to which a sample is exposed. The dosimetric response of the REIC can consequently also depend on air-kerma rate, since charge lost from the electret due to radiation induced conductivity can be mistaken for charge transferred strictly through the chamber air-gap. However, having come to an understanding of the effects of radiation induced conductivity, we are now able to minimize them by stipulating that a sufficiently low electric-field strength be maintained in the electret. This can be accomplished either by limiting the electrostatic potential to which the electret is initially charged, or by increasing the thickness of the electret. We can also increase the thickness of the air-gap so that the fraction of charge that is lost is small in comparison with the total charge lost through the air and electret.

We are able to both prolong the useful life of a radiation charged electret and hasten the onset of the useful period by subjecting the electret to heat treatment shortly after charging. This procedure restores the electret to its pre-irradiation state by allowing the recombination of charge carriers generated by radiation, and empties the most energetically shallow trapping sites of their charge carriers. The heating conditions shown to be ideal for Teflon (FEP) electrets charged in other ways were unattainable in our experiments, but we have shown that even the mild treatment which we were able to implement markedly reduces the natural decay of the stored charge. Furthermore, we have shown that a system of rate equations developed for corona charged electrets can be fitted to the charge decay curve of an unheated radiation charged electret.
**Future Work** The model which has been used to predict the evolution of charge distributions in the REIC should be modified to account for the effects of space charge build-up that is known to exist in ionization chambers. This is certain to exist in the REIC as well, and may have a subtle effect on the way with which the electret is charged. As well, charge storage on the inner surfaces of the electret chamber should be investigated, since this may also have an effect on charge distribution.

It is also recommended that thermally stimulated current (TSC) studies be performed to determine the energy levels of charge carriers trapped on the radiation-charged electret. This will help in the determination of an optimized heat-treatment process that will ensure stable charge retention for years. As well, the parameters discussed in Section 6.2: $\mu$, $\tau_Q$, $\tau_T$, and $\tau_o$, should be measured for Teflon (FEP) at 20 °C.
BIBLIOGRAPHY


