SURFACE CHARGE CHARACTERISTICS OF A
RADIO-CHARGED ELECTRET

by

Brennan A. MacDonald

Medical Physics Unit
McGill University, Montreal
November, 1990

A Thesis Submitted to the
Faculty of Graduate Studies and Research
in Partial Fulfillment
of the Requirements for the Degree of

Master of Science
in Medical Physics

© Brennan A. MacDonald, 1990
Measurements of charge distributions across the face of isothermally, radio-charged polymer electrets are presented. The electret forming chamber is comprised of a parallel-plate ionization chamber in which the collecting electrode is covered by a dielectric (Teflon,Mylar). Charging is accomplished by the simultaneous application of electric potential and ionizing radiation to the chamber. The electret can be discharged by removing the external potential during further irradiation. For these studies the electrets are scanned with an electrostatic voltmeter probe yielding digitized maps of the surface charge as functions of time under various charging and discharge conditions. The results of numerical modelling of the charging process are compared with experimental data. Storage techniques for optimum charge retention are discussed. It is found that charge stability is comparable to that achieved through corona charging. These results allow us to design an optimum reusable, radio-charged electret-dosimeter.
RÉSUMÉ

Des mesures de la distribution de la charge de surface provoquée par irradiation isothermale d’électrets sont présentées. Le dosimètre utilisant un électret consiste en une chambre d’ionisation à électrodes parallèles où l’électrode collecteur est recouvert d’un isolant (Teflon, Mylar). Le chargement de la chambre s’effectue par l’action conjointe d’un potentiel électrique appliqué et de radiations ionisantes. La décharge de l’électret se fait en retirant le potentiel de chargement lors d’irradiation subséquentes. La charge à la surface est obtenue par balayage des électrets à l’aide d’une sonde liée à un voltmètre électrostatique produisant ainsi une cartographie numérique de la charge de l’électret qui est une fonction du temps pour diverses conditions de chargement et de déchargement. Les résultats d’un modèle numérique du processus de chargement sont comparés avec les données expérimentales. Les techniques d’entreposage menant à une rétention de charge optimale sont discutées. Il est démontré que la stabilité de la charge est comparable à celles obtenues par les électrets chargés par effet de couronne. Ces résultats nous permettent de réaliser et d’optimiser un dosimètre utilisant des électrets radio-chargés réutilisable.
The distribution of charge on the surface of electrets charged in air via x-radiation is examined. An electret dosimeter was constructed to take full advantage of this technique which allows the charging of the dosimeter, measurement of the initial charge state, use in the field, determination of the final charge state, and the clearing of any remaining signal without requiring the dismantling of the dosimeter, as is required with other electret dosimeters.

Charge distribution measurements are performed with a non-contact, high-resolution inductive technique during the charging and discharging periods of the dosimeter's life-cycle. Charge distributions are characterized by the numerical parameter curvature calculated from distribution measurements. Resolution of the order of 0.8 mm in two dimensions is offered by this technique. It is found that a uniform distribution requires significantly more charging time when large rather than small air-gaps are employed. As well, during discharge, the surface defined by charge density as a function of position on the electret surface is well modelled by a truncated cone. As discharge time progresses, the uniform central surface shrinks in area as well as charge density.

Charge distributions are modelled by finding electrostatic potentials calculated by computer-generated numerical solutions to Laplace's equation in two dimensions, and by using boundary conditions specific to the technique of radio-charging. Charge deposition was performed by mapping calculated lines of force to the surface of the electret material.

Radio-charged electrets were monitored over prolonged storage periods to measure charge decay. Electrets were stored in controlled conditions of low humidity and room temperature. Measurements were made using the same inductive technique employed for distribution measurements.
ACKNOWLEDGEMENTS

I am grateful to Dr. B. Gino Fallone for his encouragement, support, and criticism proferred during the preparation of this thesis. His contributions to the research and writing were of fundamental importance.

I also thank my colleague, Mr. Lawrence N. Ryner, for his assistance and opinions, Mr. Lajos Palotay for his help in the construction of many of the articles used in this research including the prototype electret dosimeter, and Messrs. Joe Larkin and Paul Lefebvre for help with the electrical aspects of the project.

This study would not have been possible without the financial support of The Whitaker Foundation and the Natural Sciences and Engineering Research Council, Canada. Their help is gratefully acknowledged.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>i</td>
</tr>
<tr>
<td>Résumé</td>
<td>ii</td>
</tr>
<tr>
<td>Original Contribution</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>iv</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>v</td>
</tr>
<tr>
<td>List of Figures</td>
<td>ix</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xiii</td>
</tr>
</tbody>
</table>

## Chapter 1 INTRODUCTION

1.1 Evolution of Electret Dosimetry           | 1    |
1.2 Reason for Study                          | 3    |
1.3 Scope of Study                            | 4    |
1.4 Organization of Thesis                    | 4    |

## Chapter 2 ELECTRETS AND ELECTRET DOSIMETRY

2.1 Definition                                | 6    |
2.2 Discovery                                 | 6    |
2.3 Materials                                 | 7    |
2.4 Applications                              | 7    |
2.5 Forming Methods                           | 7    |
2.6 Surface Charge Density Related to Potential | 9   |
2.7 Electret Dosimetry                        | 12   |
2.8 Efficiency of Electret Ionization Chamber | 18   |
Chapter 3 EXPERIMENTAL SET-UP AND PROCEDURE

3.1 Chapter Overview ............................................. 27
3.2 Introduction .................................................. 27
3.3 Construction of Electret and Chamber
  3.3.1 Materials and Properties of Components ............... 29
  3.3.2 Electrical Connections .................................. 31
3.4 X-ray Source
  3.4.1 Cabinet .................................................. 33
  3.4.2 Beam Shape .............................................. 33
  3.4.3 Filtration ............................................... 37
3.5 Power Supply and Electrometer .............................. 37
3.6 Electrostatic Voltmeter Probe
  3.6.1 Operation and Construction ............................ 37
  3.6.2 Probe Zeroing ......................................... 42
  3.6.3 Probe Calibration ..................................... 42
3.7 Platform ..................................................... 44
3.8 ADC .......................................................... 46
3.9 Program Description ......................................... 46
3.10 General Procedure
  3.10.1 Irradiation ............................................. 47
  3.10.2 Scanning ................................................ 47
  3.10.3 Data Processing ...................................... 49
3.11 Parameters Investigated
  3.11.1 Air-gap and Applied Potential ....................... 49
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Model for derivation of electrostatic equations.</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Parallel plate and cylindrical ionization chambers.</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>EIC system shown in charging mode.</td>
<td>16</td>
</tr>
<tr>
<td>3.1</td>
<td>Set-up for measurement of surface-charge density.</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Construction details of REIC.</td>
<td>30</td>
</tr>
<tr>
<td>3.3</td>
<td>Schematic electrical diagram of REIC.</td>
<td>32</td>
</tr>
<tr>
<td>3.4</td>
<td>Faxitron X-ray cabinet</td>
<td>34</td>
</tr>
<tr>
<td>3.5</td>
<td>Exposure versus kVp.</td>
<td>35</td>
</tr>
<tr>
<td>3.6</td>
<td>Beam profile.</td>
<td>36</td>
</tr>
<tr>
<td>3.7</td>
<td>Probe line spread function.</td>
<td>39</td>
</tr>
<tr>
<td>3.8</td>
<td>Signal deviation versus probe-surface distance.</td>
<td>40</td>
</tr>
<tr>
<td>3.9</td>
<td>Effects of tilting measured surface.</td>
<td>41</td>
</tr>
<tr>
<td>Figure 3.10</td>
<td>Variation of electret surface position.</td>
<td>43</td>
</tr>
<tr>
<td>Figure 3.11</td>
<td>Data points collected versus distance moved by platform.</td>
<td>45</td>
</tr>
<tr>
<td>Figure 3.12</td>
<td>Areas used in calculating <em>curvature</em>.</td>
<td>51</td>
</tr>
<tr>
<td>Figure 3.13</td>
<td>Expected effect of guard-ring.</td>
<td>53</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Life-cycle of REIC.</td>
<td>59</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Maximum surface-charge versus applied potential.</td>
<td>61</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Measured response during charging and discharging.</td>
<td>63</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Effects of $a$ and $V_0$.</td>
<td>64</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Non-linear and linear response.</td>
<td>68</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Charge profiles obtained during charge-up when $a = 2$ mm.</td>
<td>73</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Charge profiles obtained during charge-up when $a = 8$ mm.</td>
<td>74</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Comparison of charging at different $V_0$.</td>
<td>76</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Curvatures measured while charging REIC, $a = 2 &amp; 4$ mm.</td>
<td>77</td>
</tr>
</tbody>
</table>
Figure 5.5 Curvatures measured while charging REIC, $a = 6 \& 8$ mm. 78

Figure 5.6 Average surface potential versus charge time for different $a$. 80

Figure 5.7 Charge profiles obtained during discharge for $a = 2$ mm. 85

Figure 5.8 Charge profiles obtained during discharge for $a = 8$ mm. 86

Figure 5.9 Charge surface model. 87

Figure 5.10 Measured and calculated values of curvature. 90

Figure 5.11 Curvatures measured while discharging, $a = 2 \& 4$ mm. 92

Figure 5.12 Curvatures measured while discharging, $a = 6 \& 8$ mm. 93

Figure 5.13 Radii of uniformity during discharge 94

Figure 5.14 Central surface potentials versus discharge time. 95

Figure 5.15 Comparison of curvature and second derivative. 97

Figure 5.16 Effects of guard-ring. 98

Figure 6.1 Lattice used in numerical model. 104
<table>
<thead>
<tr>
<th>Figure 6.2</th>
<th>Boundaries used in model.</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 6.3</td>
<td>Typical calculated isopotential lines.</td>
<td>107</td>
</tr>
<tr>
<td>Figure 6.4</td>
<td>Motion of computer generated charge on model lattice.</td>
<td>109</td>
</tr>
<tr>
<td>Figure 6.5</td>
<td>Comparison of measured and calculated charge profiles.</td>
<td>111</td>
</tr>
<tr>
<td>Figure 7.1</td>
<td>Examples of calculated charge decay curves.</td>
<td>118</td>
</tr>
<tr>
<td>Figure 7.2</td>
<td>Charge decay from corona–charged electrets.</td>
<td>119</td>
</tr>
<tr>
<td>Figure 7.3</td>
<td>Charge decay after heat treatment.</td>
<td>121</td>
</tr>
<tr>
<td>Figure 7.4</td>
<td>Measured charge decay of radio–charged electret.</td>
<td>123</td>
</tr>
<tr>
<td>Figure 7.5</td>
<td>Deviation of charge distribution during discharge.</td>
<td>125</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 3.1  Effect of electrostatic scanning on surface charge.  

Table 5.1  Maximum surface potentials obtained at different applied potentials and different air-gaps.  

Table 7.1  Energy distribution of traps.  

Page

50

82

116
CHAPTER 1
INTRODUCTION

1.1 EVOLUTION OF ELECTRET DOSIMETRY

In 1954 a device known as an electret dosimeter was suggested as a possible alternative for the measurement of personnel exposure to ionizing radiation. Poor performance of the carnuba wax electret used in the original dosimeter led to refinements in materials and construction until the electret dosimeter had evolved into the electret ionization chamber or EIC. The EIC is a modified ionization-chamber, and with appropriate design can operate with high sensitivity and long exposure range. An ionization chamber can be converted into an electret dosimeter by covering one or both electrodes by a quasi-permanently charged film of dielectric material, commonly called an electret.

The electret dosimeter is durable and robust — unaffected by mechanical shock and, to a certain extent, high temperatures. Furthermore, it is lightweight and compact, and demonstrates a remarkably linear response to exposure while being relatively un influenced by the energy of radiation over a broad spectrum.

Most electret dosimeters use dielectrics charged by a process called corona charging. This requires the electret to be separated from its chamber and to be charged by passing a thin, high-tension wire over its surface. This process will be described in more detail in Chapter 2. After these dosimeters have been exposed, they are dismantled again and an electrostatic meter is used to measure the charge remaining on the electrets through induction.

A detailed explanation of the operation of the EIC in general will be presented in Chapters 2 and 4, but the key to its use is that the difference between the charge initially on the electret surface and the charge remaining after exposure is proportional to the exposure and dose. The steps involved in the reduction of the
electret charge can be summarized as follows:

(1) Ionizing radiation liberates charged particles in the air between the short-circuited electrodes of the dosimeter.

(2) Liberated ions of the appropriate polarity are drawn by electrostatic attraction to the electret, which acts as a permanent source of electric potential. During this process, the electret becomes partially neutralized by the collected ions and is left with a reduced charge density. This is known as discharge.

The work presented in this thesis represents an attempt to better understand the operation of a different type of electret dosimeter: the radio-charged electret ionization chamber (REIC). This device is inexpensive to build and simple to use. It differs from other electret dosimeters mainly in the manner in which it is prepared and read. This difference allows convenient reusability and operation without the need of dismantling the dosimeter. Its preparation and reading require items that are readily available in most hospitals and environments requiring radiation monitoring: a X or γ-ray source, a high-voltage source and an electrometer. Furthermore, as with other electret dosimeters, the charge remaining on the electret can optionally be read non-destructively by induction after dismantling the REIC.

The REIC which is built as an EIC is charged, discharged and read in virtually identical ways. To charge the REIC, the collecting electrode is covered by an initially neutral dielectric film (e.g. Mylar, Teflon), and a potential difference is applied across the electrodes. The chamber is then irradiated with photons (X or γ). Ions liberated in the sensitive volume are propelled by the electric field provided by the opposing electrode, and become trapped on the surface of the dielectric film.
This process continues until the electrostatic potential of the electret equals the applied potential. At this point the electric field has a value of zero between the electrodes, and ions created in the air recombine, and no longer drift towards the dielectric.

Once the dosimeter is charged, the external power supply is removed, the electrodes are short-circuited and the chamber is sent into a working environment to record dosimetric information. Any subsequent ionizing radiation causes charge on the electret to be neutralized. In this process, ions of opposite sign drift toward and reduce the charge on the electret surface according to the process described above in steps 1 and 2.

During the reading process, the electrodes remain shorted and whatever charge remains on the electret is discharged by intentional irradiation of the REIC with an external source of X or γ rays. The charge lost from the electret is then measured flowing out of the backing electrode by an electrometer. Once this task is completed, the REIC has completed its life-cycle and is ready to be recharged.

The loss of charge is ideally proportional to exposure, but response can stray from linearity when certain parameters are inappropriately set. One of the motivating factors behind the work described here was to study the cause of this non-linear performance and to determine possible corrective measures.

1.2 REASON FOR STUDY

For an informed decision to be made about the viability of this electret dosimeter in particular and electret dosimetry in general, it is necessary to fully understand the workings of the dosimeter and the mechanism by which it is charged and discharged. This study will help to clarify: the radio-charging technique by which the electret is prepared, the distribution and retention of charge, and the distribution of charge during discharge by ionizing radiation.
It is possible that the key to understanding the non-linear response of the radio-charged electret dosimeter that occurs under certain conditions lies in the uniformity with which charge is deposited on the surface of the electret during charging, and the uniformity with which charge is depleted during exposure. These distributions have been measured in detail and the results will be presented in the following chapters.

An additional purpose for our investigations was to determine the longevity of an electret dosimeter: the duration of the charge held by an electret that is not exposed to radiation. Obviously this will effect the length of time during which the dosimeter can be used to measure radiation.

1.3 SCOPE OF STUDY

The experiments described in this paper concern only the measurement of the effective surface charge density on thin-film, radio-charged, polymer electrets. An assumption that charges are deposited only on the surface of these polymers, as opposed to the bulk of the dielectric, is held throughout the study. This assumption is valid because of the low energy of the impinging ions. The polymers considered are Mylar and Teflon. The measurements are performed to determine the influence of various parameters on the uniformity of charge distribution at various stages during the life of the electret dosimeter: charging, discharge and decay. An attempt to predict the observed patterns has been made by way of a computer model. This seems to satisfactorily account for the patterns recorded during the charging process.

1.4 ORGANIZATION OF THESIS

The thesis is divided into eight chapters. At the end of each chapter are listed all references cited in that chapter. Chapter 2 is written to provide
information on the history and applications of electrets.

In Chapter 3, the construction of the REIC is explained, and the materials and the equipment used to create and monitor the electrets are examined. In addition, the procedure followed in the experimental process along with the computerized control of the measurement apparatus are detailed.

In Chapter 4, the full operation of the radio-charged electret dosimeter is explained. Included in this explanation is a description of undesirable, non-linear response to radiation seen when air-gaps are sufficiently large and/or when the region of interest on the electret is a sufficient fraction of the entire electret.

Chapter 5 discusses the effects of varying the air-gap and applied potential on the operation of the electret dosimeter during charging and discharging processes. This is done both in terms of how these variations affect dosimetric response and how they affect the distribution of charge. The intrinsic effect of a guard ring on charge distribution is also briefly discussed.

In Chapter 6, the basis behind a numerically calculated computer model of the electret dosimeter is presented. The results of the application of the program are then presented and discussed.

The theory behind the trapping and decay of charge on an electret surface is given in Chapter 7. Our observations of several electrets are then presented. These electrets had been stored under controlled conditions for a five month period and measurements of retained charge were made at various intervals.

In Chapter 8, results and conclusions are summarized.
CHAPTER 2
ELECTRETS AND ELECTRET DOSIMETRY

2.1 DEFINITION

An electret is defined by Sessler\(^1\) as any dielectric carrying a persistent electrical charge. The charge can be any combination of real or dipolar. Charges are considered persistent if their duration is much greater than the time frame over which observations are made. For our purposes an unexposed electret will be required to retain its charge over a number of months.

Our electrets are thin films of polymer (Mylar or Teflon), bearing a real negative charge on one surface. They are charged by a process to be described briefly in Section 2.7 and in more detail in Chapter 4.

2.2 DISCOVERY

The term electret was introduced in 1885 by Oliver Heaviside, but electrets had been first noted centuries before this date\(^2\). Observations of the behaviour of electrically charged materials date back to the ancient Greeks, who noticed the attractive forces exhibited between pieces of rubbed amber. Kinetic friction between rubbed surfaces served to transfer charge. Until recently, electret research has been confined to a relatively few individuals, notably Faraday and Volta. Interest gained momentum in 1919 with the work of Japan’s Eguchi\(^2\), who began a systematic study of electret properties. His electrets were formed of wax, resins or sulphur and were charged thermally, a process which will be described later. Investigations into possible commercial applications began with xerography in the 1940’s.
2.3 MATERIALS

Bee's wax and amber were popular electrets in the early days of research. More recently such materials as silicone dioxide (SiO₂), aluminum oxide (Al₂O₃), and a host of polymers including Teflon and Mylar have become popular. The choice of these materials is due largely to their charge capacity and stability, though ease of production and manipulation is partly responsible. Any insulating or semi-conducting material can become an electret, provided there exist localized energy traps in which charges can be held.

2.4 APPLICATIONS

The successful application of electrets relies on the electrostatic force generated by them, and the permanency of this force. As mentioned above, one of the original applications was in the field of xerography. The electret used here is a photoconductor. Thus, where light from the original image strikes the electret, charge is lost. A charge pattern corresponding to the original remains on the electret. An additional example is the electret microphone or speaker, in which the transducer mechanism of coil and magnet is replaced by capacitive plate and electret. Electrets are used in motors and generators, air filters, and as recording media. In medical imaging, ionography is a useful modality. The application to be examined in part in this study is that of the electret as a radiation dosimeter.

2.5 FORMING METHODS

As was noted above, initial efforts to produce electrets were confined to triboelectric techniques, or the transfer of charge through kinetic friction. As understanding grew, so did the arsenal of techniques from which investigators could draw to produce their electrets.

Real or space—charged electrets are generally formed via the injection into, or
deposition of charge onto, the dielectric by discharges, particle beams, or contact electrification. In the first two cases, an applied field donates sufficient energy to charged particles to propel them from the forming electrode to the dielectric surface or bulk. The latter case is similar but there is no interfacial gap to be crossed by the charged particles.

Liquid and thermal charging are commonly used methods of transferring charge. Liquid charging requires a polarizing electrode to be positioned close to the dielectric surface and a small amount of liquid placed between them to provide intimate contact. High voltage is applied to the polarizing electrode and charge is transferred through molecular interaction at the interface between liquid and polymer. It was found that one can thermally charge a dielectric by holding it at an elevated temperature while exposing it to an electric field, then bringing it to room temperature while still under the influence of the externally applied field. The dipole polarization induced by the applied field and allowed by the elevated temperature becomes "frozen-in" when the temperature is lowered.

One of the more important examples of the discharge forming technique is that of corona-charging. In this process a film or slab of dielectric is placed over a grounded electrode surface and a highly charged thin wire is passed over the surface in a direction parallel to the surface. The electric-field near the wire must be sufficiently high to cause electric breakdown of the air. The breakdown allows charge carriers to flow from the wire to the film surface where they remain trapped.

The radio-charging process used here has been described by Fallone and Podgorsak and may prove a preferable alternative to corona-charging for dosimetric purposes. The electrets produced by this method have some properties (e.g. stability) that are similar to those obtained in corona-charging, since in both cases air ions are involved. Of the two techniques, radio-charging is inherently easier as it can be performed without dismantling the dosimeter which holds the
uncharged dielectric. The charging is done by placing a dielectric film over one of the two parallel electrode surfaces, applying a potential difference between them, then irradiating the system. Ions liberated in the air gap are drawn by the applied electric field toward the appropriately charged electrodes. Further discussion is given in the section entitled Electret Dosimetry later in this chapter and in more detail in Chapter 4.

2.6 SURFACE CHARGE DENSITY RELATED TO POTENTIAL

A simplified model of the chamber and circuit facilitate the solution of Gauss' and Kirchoff's second laws to obtain the well known relationship between the density of charge trapped on the surface of the dielectric and the electrostatic potential of that surface. A required assumption is that the electrodes and dielectric extend infinitely in the x−y plane.

In order to maintain generality in the solution, we consider the space between the electrodes to be occupied by three layers of dielectric of arbitrary thickness (s₁, s₂, and p) as shown in Figure 2.1. The dielectrics contacting the electrodes have dielectric constants ε₁ and ε₂ and are considered to occupy the "gaps", while the third and middle material is of dielectric constant εₚ. Finally, a layer of charge density σ is considered to lie in an arbitrary x−y plane, a distance r from the datum surface, in the middle dielectric. This divides the dielectric into regions a and b, below and above the charge layer. If a potential V₀ is applied across the opposing electrodes, the following analysis may be validly carried out. Gauss' law can be applied to the three surfaces of interest: the two inter-dielectric surfaces and the layer of charge. The resulting expressions are:

\[-\epsilon₁E₁ + \epsilonₚEₐ = 0 \quad (2.1)\]
\[-\epsilonₚEₐ + \epsilonₚEₗ = \sigma/\epsilon₀ \quad (2.2)\]
Figure 2.1: A model for the application of Gauss' and Kirchhoff's 2nd Laws
\[-\varepsilon_p E_b + \varepsilon_2 E_2 = 0 \quad (2.3)\]

in which \(E_n\) is the electric field in region \(n (n = 1, 2, a, b)\) and \(\varepsilon_0\) is the permittivity of free space.

The application of Kirchoff's second law to the circuit depicted in Figure 2.1 yields:

\[V_o + s_1 E_1 + \tau E_a + (p - \tau) E_b + s_2 E_2 = 0 \quad (2.4)\]

when the switch to \(V_o\) is closed. Manipulation of Eqs. (2.1) to (2.4) allows one to state that

\[E_1 = \frac{-V_o/\varepsilon_1 - \sigma[\varepsilon_2(p - \tau) + \varepsilon_p s_2]/(\varepsilon_0 \varepsilon_1 \varepsilon_2 \varepsilon_p)}{(s_1/\varepsilon_1) + (p/\varepsilon_p) + (s_2/\varepsilon_2)} \quad (2.5)\]

If we now require that one gap be non-existant (say \(s_2 = 0\)), that the applied potential be removed and that the electrode opposite the remaining gap be removed \((s_1 = \infty)\) we can use Eq. (2.5) to obtain the following expression for the potential of the open surface of the dielectric:

\[V_m = -E_1 s_1 = \frac{[\sigma(p - \tau)/\varepsilon_0 \varepsilon_1 \varepsilon_p]}{[(1/\varepsilon_1) + (p/s_1 \varepsilon_p)]} \quad (2.6)\]

Further simplification makes it apparent that

\[V_m = \sigma(p - \tau)/\varepsilon_0 \varepsilon_p \quad (2.7)\]
If the charge layer is confined to the free dielectric surface, \( r = 0 \) and

\[
V_m = \sigma_0 / \varepsilon_0 \varepsilon_p
\]

(2.8)

Unless the dielectric strength of the electret is excessively taxed, it is this value that we can expect to observe when we disassemble the electret ionization chamber and measure the potential at the free, charged electret surface.

2.7 ELECTRET DOSIMETRY

The Electret Ionization Chamber (EIC) can be in the form of a cylindrical or Farmer-type ion chamber or a parallel-plate ion chamber (both shown in Figure 2.2), where one of the electrodes is covered by an electret and can be called the backing electrode. The opposite electrode is connected directly to a power-supply and is commonly called the polarizing electrode.

The basis of operation of any electret dosimeter is that the difference between net charge on the electret surface before \( Q_i \) and after \( Q_f \) exposure is proportional to the exposure \( X \). This proportionality is expressed as:

\[
Q_i - Q_f \propto X.
\]

(2.9)

Radiation liberates ions in air through both primary and secondary interactions and these ions carry electrical charge. Electrostatic attraction causes ions of the appropriate sign to be drawn toward the electret surface. Once at the surface, charge is transferred to the electret from the ions, causing the net charge on the electret to be reduced. When charge is reduced on the electret, a circuit permits the flow of current in the form of compensation charges which migrate from the backing electrode to the polarizing electrode where ions are neutralized by charge transfer.
Figure 2.2: Parallel-plate and Cylindrical Ionization chambers.
The result of exposure is a partially discharged electret. The charge remaining on the electret must then be measured.

Electret dosimeters can be used for personnel\textsuperscript{10} and area monitoring\textsuperscript{11} and commonly employ Teflon or Mylar electrets that have been charged via the corona technique mentioned earlier in this chapter. Charge density on the surface of the electret is measured with non-contact inductive techniques before and after exposure\textsuperscript{12}.

In independent studies, Dorsch\textsuperscript{13} and Pretzsch\textsuperscript{13} and Gupta et al\textsuperscript{14} investigated the energy, angular and humidity dependence of negatively corona-charged Teflon-electret dosimeters used as personnel monitors. They found the EIC to be applicable to routine use by radiation workers, but they did note some potential problems. Because of scatter from the body of the radiation worker, corrections to measurements would be necessary for photons of energies < 100 keV.

The charge stability of corona-charged Teflon EIC’s was studied by Pela et al\textsuperscript{15} and found to be adequate, with charge loss of about 0.3\% per month without heat treatment. Previous work on similarly charged electrets also shows a high degree of stability in many environments. Gupta shows that liquid-contact charged electret dosimeters lose about 0.4\% of their charge per day through self-discharge at a relative humidity of 85\%. At a relative humidity of 50\% or lower, the self-discharge is not measurable.

Techniques for the use of EIC’s as area monitors were described by Pretzsch et al\textsuperscript{16} who measured tritium concentrations in air using an EIC with grounded spacing wall. They were able to theoretically determine the value of the electric field at all points in the space of the chamber and show that the chamber operates in saturation everywhere in the sensitive volume. These techniques all allow for accurate dosimetry but prove inconvenient as the EIC must in each case be dismantled for reading and the electret can only be used for one measurement.
Pretzsch and Dorschel have also proposed a reusable electret dosimeter\(^{17}\). This dosimeter has an electrically isolated conductive plate covering the electret. The electret induces a charge separation in the plate, providing the electric field needed to drive the dosimeter. Charge is held on the plate by the field of the electret, and when the electret is removed after exposure, the charge flows from the plate and can be measured. The plate is subject to rapid charge decay and the dismantling process risks charge loss from the electret however.

The radio-charged electret dosimeter (or radio-charged electret ionization chamber REIC) proposed by Fallone et al\(^{18}\) and studied here differs from the one mentioned above in the way it is prepared and read. This difference enables the user to perform both tasks without needing to dismantle the REIC and permits the same REIC to be used repetitively.

The preparation of an REIC requires that a neutral film of dielectric cover one electrode of a parallel-plate ionization chamber. A potential difference is applied across the electrodes: negative potential applied to the polarizing electrode while the backing electrode is grounded (this polarity is preferred because of the dependence of retention time on charge sign). A schematic electrical diagram is shown in Figure 2.3. The chamber is then exposed to X or \(\gamma\) radiation. Ions liberated in the air gap then migrate along the lines of electric field toward the corresponding electrodes and negative charge is trapped on the surface of the dielectric film, transforming it into an electret. An electrometer is wired in series to the configuration and measures the compensation current in the form of charges of opposite sign flowing from the polarizing electrode to the backing electrode. The integrated current equals the charge deposited on the electret surface \((Q_t)\). The external potential is then removed and the electrodes shorted to prepare the REIC for use as a dosimeter.

After having been worn by a radiation worker, during which time the electret
Figure 2.3: Schematic diagram of EIC system in charging mode.
is partially discharged in the same fashion as in other electret dosimeters, the REIC is completely discharged by exposing the chamber to additional radiation. The electrometer is inserted between the shorted electrodes to measure the charge flowing off the electret \( Q_f \) during this final exposure. The wearer's exposure can then be calculated by Eq. (2.9) and the electret recharged in preparation for another duty-cycle.

Because exposure is defined as the charge liberated per unit mass of air, for Eq. (2.9) to be true the volume from which ions are collected (the sensitive volume) must be known and constant at all times. The finite dimensions of the REIC make this stipulation difficult to meet as the electric field lines bend near the edge of the chamber. For this reason, the backing electrode is usually divided into two electrically isolated electrodes called the collecting electrode and guard-ring.

The guard-ring surrounds the collecting electrode and helps keep the electric field lines over the collector straight and parallel. Thus for a sufficiently large guard-ring the sensitive volume is easily calculable as the cylindrical volume swept through by a projection of the collector through the air-gap to the polarizing electrode. Both the collector and guard-ring are earthed during charging and discharging, but only the current flowing into and out of the collector is measured. It should also be mentioned that the guard-ring helps reduce the measurement of leakage current during charging, since it prevents the metal edge of the collector from contacting air.

A modification of the radio-charging production technique has been proposed by Pretzsch\(^\text{19}\) who described a process whereby one electret of charge \( Q \) could be used to charge another to \( 0.5Q \) while being reduced to \( 0.5Q \). One electrode of the REIC is covered by the original electret and the other is covered with a neutral dielectric film. The chamber is assembled, the electrodes short-circuited and the system irradiated. Charge is deposited on the dielectric film at the same
rate as it is depleted from the electret until both are at equal potential.

2.8 EFFICIENCY OF THE ELECTRET IONIZATION CHAMBERS (EIC)

The efficiency of charge collection in an EIC is the ratio of charge lost from the electret surface to charge liberated by ionizing radiation or measured current over saturation current, and for a given chamber is determined by the applied potential. Very high electric fields in an EIC cause efficiencies greater than 1 and place the EIC in the gas—multiplication region, and very low fields cause efficiencies significantly less than 1 which indicates recombination of ions in the EIC.

The chamber response to radiation in either of these cases is proportional to the potential difference across the air—gap. There is a wide range of electric field in which the efficiency is 1. In this range the chamber is said to be in saturation. The significance of saturation is that, while an EIC operates in this condition, changes in potential between the electrodes do not precipitate a change in response to radiation. This steady response to radiation under a wide range of potential differences is important since the electret charge is reduced while the EIC records dose information, causing its potential to diminish. If the chamber remains in saturation, the change in surface charge will always be proportional to the exposure of the EIC.

While an ionization chamber always is expected to operate at the same efficiency under constant exposure rates, the EIC can traverse several regimes of efficiency during its exposure in the field. The usefulness of the EIC is restricted to those times when it is in saturation. Towards maximizing its usefulness, the electret is initially charged to a potential less than that necessary to cause gas—multiplication and used only as long as the charge remaining is sufficient to prevent recombination.

The dependence of efficiency on potential difference and distance between the
electrodes was stated indirectly by Mie as a solution of Thompson's equations:\(^{20}\)

\[ V = R I_{\text{sat}} (f + 1.04 f^2), \quad \text{for } f < 0.67 \]  \hspace{1cm} (2.10)

and

\[ V = 0.828 R I_{\text{sat}} [f/(1-f)]^{1/2}, \quad \text{for } f > 0.67 \]  \hspace{1cm} (2.11)

where \( V \) is the potential difference between the electrodes, \( f \) is the collection efficiency \( I/I_{\text{sat}} \). \( R \) is the ohmic resistance of the ionized gas between the electrodes and is dependent on ionic mobilities, propensity for recombination, exposure rate, and sensitive volume\(^{21}\), \( I_{\text{sat}} \) is the saturation current. The saturation current \( I_{\text{sat}} \) divided by collector area is the saturation current density \( j_{\text{sat}} \). Similarly \( I \) corresponds to \( j \).

Boag and Wilson\(^{22}\) solved for efficiency very near the saturation region as:

\[ f = (1 + n^2 a j_{\text{sat}}/E^2)^{-1}, \]  \hspace{1cm} (2.12)

where \( n \) is a parameter characteristic of the chamber configuration and the nature of the gas within, \( a \) is the air-gap thickness and \( E \) is the electric-field strength in the chamber.

Greening\(^{23}\) later found that a slight modification of Eq. (2.12) provided a better fit:

\[ f = (1 + n a j_{\text{sat}}/E^2)^{-1}. \]  \hspace{1cm} (2.13)
An equation that is valid for the whole saturation curve was developed by Fallone and Bencomo\textsuperscript{24} for continuous radiation:

\[ f = \frac{j}{j_{\text{sat}}} = \frac{(AV + BV^2) / (1 + AV + BV^2)}{f}. \quad (2.14) \]

where: \( A = \sqrt{B/1.41} \); and

\[ B = (1/0.828)^2 \frac{(\mu_1 + \mu_2)}{e^2/\alpha_0} \frac{1/2}{f_{\text{sat}}/2}. \quad (2.15) \]

where \( \mu_1 \) and \( \mu_2 \) are the mobilities of positive and negative ions respectively and \( \alpha_0 \) is the volume recombination coefficient. As was demonstrated in Section 2.6, \( V \) can be expressed in terms of surface charge \( \sigma \) by Eq. (2.8).

Eq. (2.14) is however not very useful in deriving an analytic expression for the response relationship between REIC current and time of exposure. Given a formula for response, the REIC can be calibrated with allowances made for the departure from saturation seen at the end of the discharging process, when electric fields are very low.

An alternative way of relating \( j \) to \( j_{\text{sat}} \) which allows the derivation of an analytic response formula is\textsuperscript{25}:

\[ j = j_{\text{sat}} \tanh(E/E^*), \quad (2.16) \]

where \( E \) is the electric field strength. The extrapolated electric field \( E^* \) is an empirically derived constant, determined by the intercept of the extrapolated linear portion of \( f(E) \) with the line defined by \( f = 1 \). \( E^* \) can be determined by\textsuperscript{26}.
\[ E^*(a) = k a \sqrt{\kappa \dot{X}} + m' \dot{X} \epsilon(Z,E) (1 - e^{-3a/a_r}), \]  

(2.17)

where \( k \) is a universal parallel-plate ionization chamber constant equal to \( 12.4 \times 10^5 \) \( V/(A \ cm)^{1/2} \), \( m' \) is the product of \( \lambda' \) (defined below) and \( m \) the empirically derived slope of the curve of \( E^*(a=\infty) \) versus photoemission saturation current density \( J_{\text{sat}}(\infty) \), \( \kappa \) is a constant of proportionality \( 3.33 \times 10^{-10} \) As/cm\(^3\)R, \( \dot{X} \) is the exposure rate in units of R/s, \( a_r \) is the range of photo-electrons generated by photons of energy \( E_p \) in air at normal temperature and pressure, and \( \epsilon(Z,E) \) is the efficiency with which back-scattered electrons are ejected. Similarly, \( J_{\text{sat}} \) can be expressed as a function of air-gap:

\[ J_{\text{sat}}(a) = \dot{X}(\kappa a + \lambda') \epsilon(Z,E) (1 - e^{-3a/a_r}). \]  

(2.18)

where \( \lambda' \) is an experimentally determined constant equal to \( 1.33 \times 10^{-6} \) C/Rcm\(^2\). Efficiency curves for air-filled ionization chambers show a slower approach to saturation than Eq. (2.16) predicts, however the calculated values are acceptable for our purposes.

2.9 EIC OPERATION IN SATURATION

If an EIC is assumed to be operating in saturation, and the electric field \( E \) is directionally uniform throughout the chamber, then the rate at which the surface-charge density \( \sigma \) changes with exposure \( X \) (R) is given by\(^27\)

\[ \frac{d\sigma}{dX} = K \rho a, \]  

(2.19)

where \( \rho \) is the density of air, \( a \) is the electrode separation and the constant \( K \) is a
dimensionless constant of proportionality equal to $2.58 \times 10^{-4}$. Such a situation is hypothetical and can be achieved only by parallel plate electrodes of infinite area. Eq. (2.19) clarifies the dependence of the sensitivity and range of the EIC on the value of $a$. Ignoring non-linear effects, it is obvious that, if the size of the air-gap is increased, the sensitivity or amount of charge lost per unit of exposure is increased proportionately, enhancing the difference between initial and final charge-densities. However, since there is a limited amount of surface-charge to draw from, the range or the exposure necessary to completely nullify the surface-charge is reduced when the size of the air-gap is increased.

An increase in sensitivity can also be realized by an increase of the electret surface-area. This does not alter the dependence of surface-charge density on exposure, but does increase the collection volume and thus the current measured for a given exposure rate, thus amplifying the difference between total charge measured flowing onto the electret during charging and the remaining charge effluent upon discharge. The size of the electret is only limited by a person's desire/ability to wear the device. As will be indicated, the greater size of the electret also helps maintain linear performance. Yet another technique available for the enhancement of EIC sensitivity is the manipulation of the thickness $p$ of the electret itself. Since the saturation current does not change with foil thickness, and maximum charge density is (normally) inversely proportional to foil thickness, the charge available per unit exposure is also inversely proportional to $p$.

The range $R$ of measurable exposure (in R) is proportional to the initial potential of the electret $V_o$

$$R = \frac{V_o}{\frac{dV}{d\lambda}}$$  \hspace{1cm} (2.20)
where \(dV/dX\) is the sensitivity and is considered constant for all \(X\). Because of the proportionality between \(V\) and \(\sigma\), Eq. (2.19) can be stated:

\[
dV/dX = K\rho a, \tag{2.21}
\]

and Eq. (2.20) can be substituted into Eq. (2.21) to yield

\[
R = V_o/K\rho a. \tag{2.22}
\]

So we see that range is proportional to the nominal electric field \(V_o/a\). This implies an absolute limit on range since there is a maximum electric field magnitude \(E\) determined by the dielectric strength of the air and electret and charge multiplication.
REFERENCES


12. B. Dorschel and G. Pretzsch, "Properties of an Electret Ionisation Chamber For


CHAPTER 3
EXPERIMENTAL SET-UP AND PROCEDURE

3.1 CHAPTER OVERVIEW

This chapter begins with a brief summary of our experimental procedure, followed by a description of the construction of the REIC. Afterwards, the X-ray source, the power supply and the electrometer which were used are described. The Electrostatic Voltmeter Probe and the motor-controlled X-Y platform used to measure surface charge density are then presented. Next, the software used to control our equipment and analyze our data is detailed. Finally the steps taken in our experimental procedure are summarized.

3.2 INTRODUCTION

Our electrets are charged in a Hewlett-Packard Faxitron X-ray cabinet\(^1\) by the method described in Chapter 2 and this chapter. A DC voltage source is employed to provide the electric field which drives the charging process. The chamber is then dismantled and the electret surface-potential is mapped using a Trek electrostatic voltmeter probe (Model 344)\(^2\) held over the electret surface by a test-tube clamp attached to a retort stand. An Aerotech\(^3\), servo-driven X-Y platform is used to move the electret while it is beneath the probe, which offers 0.8 mm resolution in each direction. This set-up is illustrated in Figure 3.1. Each data point acquired by the probe has assigned to it the relative position of the probe over the electret at the time of measurement, and thus a voltage map is produced.

Charge distributions that are found during both the charging and discharging processes are studied in this way. As well, this measurement technique is used to track the decay of charge stored on the electret surface as a function of time when the electret is not being irradiated.
Figure 3.1: Charged electret mounted on X–Y platform with probe positioned above.
3.3 CONSTRUCTION OF ELECTRET AND CHAMBER

3.3.1 Materials and Properties of Components

The chambers which house the electrets comprise two circular, fiberglass end-walls (5.1 cm in diameter and 0.75 mm thick) and a cylindrical, bakelite spacer ring used to separate the walls. The spacers are of 5.1 cm outside-diameter, 3.8 cm inside-diameter and of various heights $a$. Figure 3.2 shows the construction of a typical chamber.

Double-sided tape (0.125 mm) is used to affix the electrodes to the end walls of the chamber. The walls are prepared by first covering them with the tape. Enough is applied that excess protrudes beyond the edges of the disk. Then a thin conducting foil is adhered to one wall, forming the polarizing electrode, and a polymer foil bearing a vacuum-deposited aluminum layer is adhered to the other wall such that the aluminum is situated between the wall and polymer foil. A scalpel is used to cut away excess tape and foil leaving all edges flush on each wall. Three holes are drilled through each disk close to the edge and spaced at angles of 120° allowing the chamber to be held together by nylon screws (type 6-32). It is assumed that, owing to the material and location of the screws, they will have an insignificant affect on the operation of the chamber.

Electrical contact with the outside world is facilitated by small (1 mm diameter by 3 mm long) segments of copper wire, one per wall. These pass through close-fitting holes in the chamber end-walls 2mm from their edges, and are nearly flush with the inner surfaces of the walls. A grinder is used to 'mushroom' the ends protruding from these surfaces to ensure that the wires cannot be forced backwards through their holes. Conducting cement is applied to the interface between wire and electrode, and contact is assured by the spacer-ring which presses against the electrode at this point. On the outer side of the walls, female pin-connectors are soldered to the protruding wire segments and all metal surfaces are insulated from
Figure 3.2: Construction of a REIC: (a) plan and elevation views, (b) exploded and enlarged elevation view.
the air to prevent charge from flowing through ionized air directly to the electrodes.

Three types of dielectric are used in this study. Two are Teflon PTFE (polytetrafluoroethylene) (dielectric constant $\epsilon = 2.1$): in formats of either 76 $\mu$m thick tape, or 25 $\mu$m thick foil. The Teflon tape is coated with adhesive on one side and is applied to a thin (0.011 mm) aluminum foil electrode. The Teflon foil has a thin (on the order of $\AA$) aluminum electrode condensed on to one surface. These electret materials were both included in the study of charge lifetime, but due to time restrictions were excluded from studies of uniformity. The final type of dielectric is Mylar ($\epsilon = 3.2$), which is in the form of a 110 $\mu$m foil onto which has been evaporated the aluminum electrode. Though Mylar is the dielectric studied with regard to charge distribution, it is felt that owing to the thinness of the polymer–film, the lines of $E$ will not vary much between different polymers and much of what is observed can be seen on films of other polymer materials.

3.3.2 Electrical connection and circuit

All metal surfaces, other than the free surface of the polarizing electrode, are prevented from coming into contact with air. It is important that no path exist in air connecting the two electrodes. This ensures that only that charge deposited on the dielectric surface (and that which travels through the dielectric itself as a result of radiation–induced conductivity) is measured as current during the charging or discharging processes. This sealing is accomplished by generously applying epoxy to the soldered connections outside the chamber and enveloping the pin connectors in shrink–fit plastic tubing. A diagram of the chamber in its charging/discharging–measuring circuit is shown in Figure 3.3.

During operation, leads which pass via a maze through the rear wall of the X–ray cabinet are connected to the electrodes of the assembled chamber. Current flows across the chamber gap, through a Keithley electrometer, operating as an
Figure 3.3: Electrical circuitry of REIC and support apparatus in charging mode.
ammeter, through ground, to a high-voltage source, and back to the chamber.

3.4 X-RAY SOURCE

3.4.1 Cabinet

The Faxitron X-ray cabinet—model number 43855A1 houses a self-rectified X-ray tube and is capable of continuous operation over very long exposure times. Figure 3.4 depicts an REIC being irradiated in the Faxitron. The tube current and peak potential can be controlled independently by the operator, though 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 achieved and can be maintained over exposure times on the order of one hour. Figure 3.5 shows the exposure rate in air (R/min) measured on the beam axis at a distance of 53 ± 1 cm from the focal-spot and at a tube current of 3 mA as a function of kVp. Most of the data represented in this study were obtained at an arbitrarily chosen tube-potential of 93 kVp.

3.4.2 Beam shape

The beam profile at the standard source-to-chamber distance of 53 cm is measured using film and a digitizing densitometer. Kodak XV film is exposed at 93 kVp for 0.33 min. and the resulting optical density is recorded with a CCD video camera then entered into computer memory. The results can be seen in Figure 3.6 where relative exposure is plotted as a function of position. The exposure was chosen such that the film would be in the linear portion of its response curve when irradiated. The beam is seen to be quite uniform across a central circular area of 10 cm diameter—the area in which the EIC is placed during both the charging and discharging processes.
Figure 3.4: Irradiation of REIC in Faxitron X-ray cabinet.
Figure 3.5: Exposure rate plotted vs. kVp at 53 cm from target (shelf level) in Faxitron
Figure 3.6: Beam profile at a target distance of 53 cm, and beam strength of 93 kVp
3.4.3 Filtration

Filtration is provided by 0.64 mm of beryllium and an additional 3 mm of aluminum placed 16 cm above the chamber. The beam strength at 93 kV_p is a half–value layer (HVL) of 2.0 mm of added aluminum. A calculation of equivalent beam energy can be carried out by calculating the mean attenuation coefficient $\bar{\mu}$ from:

$$\bar{\mu} = \ln(2)/\text{HVL}$$  \hspace{1cm} (3.2)

and then consulting a published table of attenuation coefficients. The effective beam energy of our source operating at 93 kVp was found through interpolation to be 29.2 keV.

3.5 POWER SUPPLY AND ELECTROMETER

Power is supplied to the chamber by a Keithley–245 High–Voltage Supply, capable of putting out DC voltage from 0 to 1999 V in increments of 1 V. Measurements during operation are performed by a Keithley–35617 Programmable Dosimeter. This device can be used as a digital ammeter, integrating ammeter or voltmeter, converting analog input to digitized output.

3.6 ELECTROSTATIC VOLTMETER PROBE

3.6.1 Operation and Construction

The Electrostatic Voltmeter (ESVM) relies on the motion of a dynamic, compensating capacitor to measure the local electrical potential of a surface placed beneath it – a technique already used to measure surface–charge distributions on corona–charged, Teflon electrets. An amplified signal, the value of which is 1/100 of the measured voltage, is then put to an analog–to–digital converter (ADC).
The capacitor is housed in a probe which is wired to the body of the ESVM. The "window" through which the capacitor senses the surface beneath it is $0.78 \pm 0.005$ mm in diameter.

The dynamic capacitor relies on an AC signal applied to a piezoelectric crystal to set it in oscillatory motion (with a frequency of approximately 700 Hz). The capacitive plate is rigidly attached to the crystal. When the vibrating plate is subject to an electric field, it generates an AC signal which acts as input to the ESVM. A difference-amplifier augments the signal and sends it to a feed-back loop. The feed-back is used to change the DC potential of the plate — at a rate dependent on the potential difference between plate and surface — so that the potential difference decreases.

When both surfaces are at an equal potential, a zero electric field exists and the DC voltage of the plate stabilizes. The process requires a maximum of 2 ms to reach 2000 V. Ideal operation is achieved in a completely uniform electric field, with the ratio of probe-to-surface distance to plate size as small as possible. Information transfer capabilities decrease, and noise increases with probe-surface distance (PSD). Figure 3.7 shows several line spread functions obtained at different PSD’s. The "line" voltage was supplied by a thin (0.15 mm) wire charged to 200 V. The full-width-at-half-maximum (FWHM) of the functions indicate a minimum spatial resolution of about 0.8 mm at 0.3 mm PSD.

As can be seen in Figure 3.8 the standard deviation of a set of measurements procured when the probe is positioned over a stationary, uniformly charged conducting surface clearly rises with increasing PSD. Thus the signal-to-noise ratio is strongly dependent on the PSD, with much information lost at high PSD.

Beyond these dependencies, the mean measured value of surface voltage shows a slight linear dependence on PSD. This was observed when a smooth, tilted conducting surface was mounted beneath the probe and a curve of measured voltage
Figure 3.7: A series of LSF’s, taken for 3 different probe distances from a 0.15 mm wire charged to 200 V.
Figure 3.8: Standard deviation of 100 potential readings taken over a charged conducting surface vs. probe–surface–distance.
Figure 3.9: Probe reading vs. position over tilted conducting surface.

\[ V_m = V_{m_0} - kx \]

\[ k = 0.05 \text{ V/mm} \]

\[ V_{m_0} = 199.92 \text{ V} \]

\[ V_0 = 200 \text{ V} \]
versus position obtained – seen in Figure 3.9. Though the dependence probably
decreases with larger mean PSD, it is clear that the need to minimize probe noise
requires that mean PSD should be maintained as small as possible. This
dependence raises questions about noise in the surface–voltage measurements due to
undulations in the electret surface.

To determine the deviation of the electret surface elevation from the mean, a
depth–gage indicator was substituted for the ESVM probe in the clamp jaws.
Height measurements were made at 17 different locations along two perpendicular,
radial lines. The resulting curves are shown in Figure 3.10. From this data, a
standard deviation of 0.01 mm was obtained. When this value is used to calculate
the voltage–noise due to surface variation, a deviation of 0.073 V is obtained. This
is much less than the inherent noise of 0.55 V observed at a PSD of 1 mm.

3.6.2 Probe zeroing

A control is provided on the ESVM which permits the user to shift the
output up or down, thus when measuring the potential of a known surface, the
output can be adjusted to the proper value. This process is automated in our
scanning procedure. A grounded surface is scanned before scanning the electret
surface. The measurements from the grounded surface are then averaged and the
mean is subtracted from every measurement obtained over the electret.

3.6.3 Probe Calibration

A separate control allows the gain of the output to be adjusted. Once the
probe is known to have been properly zeroed, the output can be calibrated by
measuring the potential of a known surface and adjusting accordingly. Frequent
checks revealed that, once set, the gain alters imperceptibly, if at all.
Figure 3.10: Plot of typical variation of surface height with position (in 2-d) across electret.
3.7 PLATFORM

The X-Y platform is a servo-motor operated unit produced by Aerotech. It is controlled by a two-axis microprocessor-based motion controller (model Unidex 11, U11s). The controller can be programmed from its front panel, or from a program supplied externally via an IEEE488 Interface Bus, or can be operated interactively via the same bus. Platform velocity and acceleration can be specified. Velocities can be set from 0 to 101.6 cm/s. The minimum acceleration time is 10 ms. Distances can be specified to 2 μm.

Investigations of the effect of acceleration time on data-acquisition were performed. Results from measurements of the number of data-points collected during the motion of the platform as a function of distance moved by the platform are shown in Figure 3.11, for a platform speed of 0.102 cm/s, and an acceleration time of 250 ms. The commencement of platform motion is coincident with the beginning of data acquisition, and the platform's halt triggers the cessation of data collection. As expected, linearity between the two is observed. A slightly convexly curved beginning, shows that acceleration time has less effect on the total number of data points the longer the distance moved by the platform. The rate at which the ADC converts data-points is dependent on the potentials it converts and their fluctuation, resulting in some deviation from the straight line.

Attached to the platform surface is a brass frame in which the charged electrets are inserted. A shallow recession is cut into the frame, allowing the electret with its backing electrode and supporting wall to fit snugly. The depth of the recession ensures that the charged surface of the electret is flush with the surface of the surrounding frame. During an electret scan, the frame and the electret’s backing electrode are grounded in order to supply a known reference potential.
Figure 3.11: Number of data points collected by probe versus distance moved by platform.
3.8 ADC

An Iotech analog-to-digital converter (ADC) model ADC488/8s is used to convert analog data signals imported from the ESVM to digital format for export to computer memory and subsequent analysis. The ADC is capable of 100,000 conversions per second when one input line is being sampled. It is also controllable via the IEEE488 bus from an external processor. The program that runs the motion controller also initializes the ADC, sets the sampling rate and sends signals triggering the acquisition of data for transmission to computer memory.

3.9 PROGRAM DESCRIPTION

All programming was carried out in TurboPascal language on either an IBM-type XT or AT386 which was used exclusively soon after the beginning of the study. Software written for this study is listed in Appendix A. The data-acquisition program drives the platform to an initial reference point such that the probe window is directly over one corner of the brass frame. A small mirror is then used to confirm the probe's correct positioning. One edge of the grounded frame is scanned and the data used to establish a reference point for comparison with subsequent voltage measurements. This completed, the program positions the platform such that the probe will be directly over the corner of a 32 mm x 32 mm square, centered on the electret. Scanning then commences, with the platform moving in a television raster fashion, over 64 lines, spaced 0.5 mm apart, and 32 mm long. The result is a set of 4096 (64^2) data points stored in ASCII code.

Another program is then used to provide a preliminary analysis of the data. It determines whether the number of data points per line deviates from the expected 64, and if it does by how many. If the number in a line is less than 64, interpolated values are inserted at regularly spaced intervals. Similarly, if the number exceeds 64, points are extracted at regular intervals. The scanning program is designed in
order that the nominal number of data points returned to the computer per line is 64, but slight fluctuations in sampling rates make this data preparation necessary.

3.10 GENERAL PROCEDURE

3.10.1 Irradiation

Each electret is charged according to the same procedure. The free dielectric surface is first cleaned using alcohol or acetone and wiped with a lint-free tissue. The electret—chamber is then assembled with the chosen spacer—ring, and the nylon screws and nuts. The chamber is placed in the Faxitron X-ray cabinet, with precautions taken to place the chamber in the center of the beam area and perpendicular to the beam axis. For the sake of consistency, the chamber is always given the same orientation i.e. with the dielectric on the upper wall, or the X-ray photons entering the chamber through the dielectric and exiting through the polarizing electrode. The chamber is then connected to the appropriate leads, and the door to the cabinet closed.

The time of irradiation to within 1 second precision, and the peak tube potential are then chosen, and the cabinet is energized. During irradiation, tube current must be held constant by the investigator. He may do so by compensating for any loss of current (due to tube heating) with a separate control.

3.10.2 Scanning

Once irradiation is completed, the chamber is disconnected and removed from the cabinet. Scanning usually immediately follows irradiation, but some time may be allowed to elapse before the scan is performed without losing the charge resident on the electret. Prior to the scan, the chamber is disassembled and the wall bearing the newly formed electret is placed in its frame on the X—Y platform. Double-sided tape holds the wall to the frame and prevents motion of the electret
relative to the platform. A possible placement error of ± 0.5 mm can occur when adhering the wall to its frame. As a final preparation for scanning, a grounding lead is connected to the electret—backing electrode, otherwise charge accumulated on the back of the wall will affect the measured values. A probe—surface gap of 0.2 mm was the smallest reliably obtainable spacing. Occasionally the probe—surface distance is verified by placing an un—charged electret in its frame beneath the probe and using a paper spacer to reset the gap. The development of a precisely controllable positioning system is recommended.

Scanning takes place at a speed of 1.63 cm/s and a ramp—time (acceleration and deceleration time) of 10 ms. With approximately 66 (± 1) data—points procured per 32 mm scan—line, there is a spatial gap of 0.5 mm between points. Since a scan line requires 3.20 cm/(1.63 cm/s) = 1.96 s, the temporal spacing of the data points is 0.03 s. Also, since the required acceleration time is 0.01 s, only the spacing of the first column of data is is distorted, making the charge—image slightly compressed at the sides (between the first and second columns spacing is 0.041 cm instead of 0.049 cm). The effect of this distortion is negligible for our purposes. Were it necessary to avoid this artifact, the scan could be started a sufficient distance before the area of interest such that acceleration was completed before scanning of the important region had begun.

The refinement of measuring techniques and the introduction of more sophisticated hardware reduced the scanning time from several hours to three minutes. Even so, the electret preparation and data processing are time consuming activities and restricted the time resolution with which the electrets could be observed.

The process of scanning is entirely non—invasive. This was shown by a simple experiment. An initially neutral electret was charged under normal conditions two times, the integrated current measured and recorded each time. The
first time, it was discharged immediately afterwards and again the integrated current was measured and recorded. The second time, discharge was preceded by a normal scanning procedure, but again the effluent charge was recorded during discharge. When compared, the ratios of charge-in to charge-out were identical showing that no charge had been lost due to the scanning process. These values are tabulated in Table 3.1. It was necessary to charge twice, rather than simply compare in-flowing and out-flowing charge during one cycle, because of leakage current and/or radiation-induced conductivity observed in that particular chamber.

3.10.3 Data Processing

The data is then operated on by a program which divides the scanned area into 30 concentric rings of incremental radius 0.5 mm. The values of the data-points acquired from the area represented by each ring is then averaged and a mean potential-profile is obtained. The deviation of the values measured around each ring is incorporated into the value of the expected error. This process is in effect identical to taking many radial scans and averaging the results.

A working-indication of curvature (i.e. the curvature of the mean voltage profile across the electret) is chosen as the difference between the mean potentials of a small central circular area and a larger concentric ring, shown schematically in Figure 3.12. The radii are chosen according to the scale of curvature.

3.11 PARAMETERS INVESTIGATED

3.11.1 Air-gap and Applied Potential

Two of the variable parameters involved in the formation and discharge of radio-charged electrets are the chamber air-gap, \( a \), and the applied voltage, \( V_o \). The air-gap is the perpendicular distance in air separating the two electrodes, and the applied voltage is the potential applied to the polarizing electrode during the
Table 3.1. Charge In and Out of chamber with and without scanning between steps.

<table>
<thead>
<tr>
<th></th>
<th>With Scan</th>
<th>Without Scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge in (nC)</td>
<td>140.65</td>
<td>139.52</td>
</tr>
<tr>
<td>Charge out (nC)</td>
<td>115.71</td>
<td>113.90</td>
</tr>
<tr>
<td>Ratio In/Out</td>
<td>1.216</td>
<td>1.214</td>
</tr>
</tbody>
</table>
Figure 3.12: Areas over which measurements are procured and averaged.
charging process and the surface potential of the electret after charging. The effects of changes in these parameters were investigated in this study. An REIC is charged with a given $V_o$ and $a$, and at various intervals in the charging process, the electret is removed from the chamber and scanned. This is carried out for a range of potentials and air-gaps. Once fully charged, the same REIC's are discharged and the same data acquisition procedure is followed. The charge profiles and curvature are then examined.

3.11.2 Guard–ring

The effects of the ammeter on potential difference between the guard–ring and collector electrodes are measured by obtaining charging data from an REIC charged with a guard–ring and from one charged without a guard–ring. Ideally, both electrodes would sit at the same ground—potential, but the small potential drop across the electrometer/ammeter may affect the continuity of charge deposition across their common boundary as shown in Figure 3.13. This is tested by charging electrets identical except for the presence of a narrow etch separating collector from guard–ring on one, the entire surface of the other is considered the collector. The guard–ring is connected directly to the ground provided on the high—voltage source, while current from the collector must pass through an electrometer before going to ground. This effect was described for ionization–chambers\cite{12} where a guard–ring which carries a potential lying between those of the collector and polarizing electrode (as can be expected when the slight resistance of an ammeter hinders the passage of current to ground) will cause an increase in the sensitive volume, with the added volume feeds the edge of the collector. This may be seen as a rise in surface—charge density near the edge of the collecting electrode.
Figure 3.13: (a) Expected profile with guard-ring (b) expected profile without guard-ring.
3.11.3 Charge Decay

Charge life–time is measured by storing the electret in controlled conditions, and scanning at intervals in storage–time. Interval length is commensurate with charge stability: short when changing, long when steady. Desiccating crystals and an air–tight bowl provide the controlled conditions for our measurements. The entire EIC is placed still–sealed in the bowl. The bowl has a volume of \( \approx 1.7 \times 10^3 \) cm\(^3\), and the interface between bottom and top is sealed with vacuum grease. When fresh, the crystals maintain an atmosphere of \( \approx 10 \% \) R.H.. After three months' use, humidity rises to \( \approx 18 \% \) and the crystals are recharged (an annealing process requiring \( \approx 1 \) hr at 90\(^0\) C).

The same scanning and data–handling programs as used for determining the charge distribution are employed for monitoring the decay of charge. At the time of scanning the EIC is disassembled and the electret mounted on the X–Y platform, precautions being taken to ensure that the electret surface does not contact any solid or liquid surfaces. After scanning, the EIC is reassembled and sealed in the desiccating chamber. The average charge in a central area of 490 mm\(^2\), as well as the standard deviation of the charge patterns in those areas, is tracked over a period of several months. This is to record not only any reduction in charge but any redistribution, should it occur.

Several charging parameters were varied for the observation of charge decay. Two types of dielectric were used: Teflon PTFE and Mylar. Of the Teflon, two thicknesses were used: 76 \( \mu \)m and 25 \( \mu \)m. Some electrets were heated before, and at different points during, the charging process in an attempt to stabilize the charge. Some electrets were cleaned before charging, and others intentionally dirtied with finger–prints, dust etc. These investigations represent a very small part of a proper study.
of the effects these parameters have on charge retention properties of the radio-charged electret. Efforts here are to determine the general order of magnitude of time of retention, and to verify that these times are comparable to those times observed of corona-charged electrets.
REFERENCES

1Hewlett-Packard, McMinnville Div., McMinnville, Oregon, 97128

2Trek, Inc., Medina, N.Y., 14103

3Aerotech, Inc., Pittsburgh, PA, 15238–2897

4I.E. DuPont de Nemours & Co.

535617 Programmable Dosimeter, Keithley Instruments Inc., Cleveland, OH, 44139

6L.R. Ryner, unpublished data, 1990

7Sanyo Electric Inc., Compton, CA, 90220

8High Voltage Supply, Keithley Instruments Inc., Cleveland, OH, 44139


10Aerotech, Inc., Pittsburgh, PA, 15238–2897

11IOtech Inc., Cleveland, OH, 44146

CHAPTER 4

THE RADIO-CHARGED ELECTRET DOSIMETER

4.1 INTRODUCTION

In Chapter 2 we discussed the operation of the EIC in general and introduced the radio-charged electret ionization chamber (REIC). Now we will consider in greater detail the REIC. It is charged and read differently than the general electret dosimeter, but both record dosimetric information in the same fashion, and in both cases dosimetry requires knowledge of charge before and after exposure. The life-cycle of the REIC can be divided into three distinct phases. Listed chronologically these phases are: charging, exposure-in-the-field (to the radiation to be measured) and discharging. In both of the final two phases the electret is discharged, but the latter discharging process is intentional and controlled, designed to enable measurement of the charge remaining on the electret after the exposure-in-the-field.

4.2 THE REIC LIFE-CYCLE

The radio-charged EIC is a novel type of EIC. What separates the two is the way in which the REIC receives a freshly charged electret and the way in which dose is read. Other EIC's must have their electrets formed via a process requiring technology and apparatus that are separate from those used in reading the measured dose. Also, the electret material must be physically separated from the EIC during these processes. The REIC can be charged and read in nearly identical ways, and all charge values can be measured without opening the chamber housing the electret.

The radio-charged electret can spend its entire life-cycle and be prepared for a new one while safely sealed in the REIC. To facilitate this, the quantities $Q_i$ and
$Q_f$ are measured by an electrometer as integrated current flowing across the chamber during charging and discharging, respectively.

The dynamics of a REIC were described by Fallone and Podgorsak. An adaptation of this description is shown in Figure 4.1. In this diagram, two of the three distinct stages of the electret's life-cycle are depicted: charging (regions i & ii) and discharging (regions iii & iv), whereby the initial and final charge are measured, respectively. Part (a) of the figure shows the flow of current through the REIC as a function of time, Part (b) shows the charge-density, Part (c) indicates the application of external potential as a function of time, and Part (d) shows the time during which constant exposure is applied. In region (i), we see that when constant external potential and ionizing radiation are applied to the uncharged REIC, current flows at a constant rate, and the surface-charge density on the electret rises linearly along with its surface potential. This constant current requires that the electric field generated by the difference between $V_0$ and $V$ lies in the wide saturation region. Eventually enough charge is trapped on the electret surface to make its contribution to the electric field equal and opposite to that of the externally applied potential. At this point, the net field is zero (Region ii) and the collection efficiency falls rapidly from the saturation region to zero. Consequently current drops to zero and surface-charge density stops growing, levelling off at $\sigma_{max}$. In this way a freshly charged electret is produced.

Mathematically, after the electret has been fully charged, one can expect that since no potential difference exists between the electrodes $V_m = V_0$ and Eq. (2.8) can be restated:

$$\sigma = V_0 \varepsilon_o \varepsilon / \rho.$$  \hspace{1cm} (4.1)
Figure 4.1: Dependence of (a) current $i$, and (b) surface-charge density $\sigma$, on (c) applied potential $V_0$ and (d) exposure rate $\dot{X}$ in a linear REIC.
The limitations on the charge density imposed by the finite number of available traps are described by an empirically derived expression resembling a Schottky or Poole–Frenkel equation:

\[ \sigma_{\text{max}} = 2 C_e v_B^{1/2} \left[ \left( V_o + v_B \right)^{1/2} - v_B^{1/2} \right], \]  

(4.2)

where \( C_e \) is the electret specific capacitance \( (C_e = \epsilon_r \epsilon_0 / \mu) \) and \( v_B \) the breakpoint voltage. Since \( v_B \) is close to 1000 V for Teflon, and our measurements are all at or below 800 V, \( \sigma_{\text{max}} \) can validly be assumed to be proportional to \( V_o \). This function is plotted for Teflon in Figure 4.2. The significance of Eq. (4.2) is that after the traps begin to fill, the maximum surface–charge density obtainable is no longer as predicted by Eq. (4.1). While the maximum obtainable surface–charge may not always be proportional to the applied potential, the measured voltage will always be proportional to the surface–charge.

Charging at an interface between materials of differing atomic numbers \( Z \) when irradiated by X-rays, has been predicted\(^2\) and measured\(^3\) with positive charge on the side of higher \( Z \) regardless of direction of X-rays. When the two materials are the polymer layer and the ground electrode, the charge layer resulting from irradiation with our 93 kVp photons is expected to be close enough to the ground electrode to have negligible effect at the free surface of the electret (recall from Eq. (2.7) that the potential at the free surface is proportional to the distance of the charge layer from the ground electrode). Verification of the insignificance of this effect is the subject of another study.

To begin discharge, either to record exposure or measure the remaining charge after exposure, the external potential is removed, and the chamber short–circuited. Ions are consequently pushed in the opposite direction by the charge embedded on the surface of the electret, causing depletion of charge (Region
Figure 4.2: Dependence of maximum surface-charge on applied potential.
(Adapted from Fallone and Podgorsak).
This process is carried out until the remaining net charge on the electret surface is nearly nonexistent, at which point collection efficiency again falls to zero and current vanishes (Region iv). The ideal REIC is easily approached with correct choice of air-gap and guard-ring (see Section 4.5). Current measurements procured from an REIC are shown in Figure 4.3. The parameter values were: $a = 2 \text{ mm}$, $V_0 = 170 \text{ V}$, $r = 5 \text{ mm}$, $g = 15 \text{ mm}$ where $r$ is collector radius and $g$ is guard-ring size. Current is very nearly constant for the bulk of the charging and discharging processes.

An anomaly is observed at the beginning of both the charging and discharging processes. The absolute value of the current jumps to its saturation value when irradiation begins, but shortly (0.5 s) after, drops sharply then rises again, resulting in a spike. The cause of this disturbance is unknown (it could possibly be an instrumentation problem) and is beyond the scope of this study, but warrants future investigation.

A demonstration of the effect of air-gap and applied potential on sensitivity and range is provided in Figure 4.4, where the current measured from a linear REIC during charging is plotted as a function of exposure for a 2 mm air-gap and $V_0 = 200 \text{ V}$, 4 mm air-gap and $V_0 = 200 \text{ V}$, and 4 mm air-gap and $V_0 = 400 \text{ V}$. The area under each curve is proportional to the change in charge on the electret surface. Note that when the applied potential is doubled, the area beneath the current curve (the range) is doubled. When the air-gap is doubled, the saturation current (sensitivity) is doubled, but the area remains constant.

### 4.3 DYNAMICS OF THE REIC

The REIC's charging and discharging curves as functions of time are expressed well by the relationship: 

$$\ldots$$
Figure 4.3: The response of a radio-charged EIC to radiation during (a) charging and (b) discharging.
Figure 4.4: Effects of changing $a$ and $V_0$ on sensitivity and range of an REIC.
where \( j_{\text{sat}} \) is the electret chamber saturation current density derived in Chapter 2, and \( \tau \), the dielectric relaxation time, and \( t_0 \), characteristic polarization time, are given by

\[
\tau = \epsilon_0 (a \epsilon_p + p \epsilon_a) E^*/p j_{\text{sat}},
\]

(4.4)

and

\[
t_0 = \tau \ln \sinh[E_a(0)/E^*],
\]

(4.5)

In Eqs (4.4) and (4.5), \( p \) is the polymer thickness, \( E^* \) the extrapolated electric field and \( E_a(0) \) the applied electric field in the air-gap. The extrapolated electric field is obtained from the intercept of the linear portion of the curve of efficiency vs. electric field. Eq. (2.16) was used to derive Eq. (4.3) which describes the rapid reduction of current that occurs at the end of charging and discharging.

### 4.4 CALIBRATION OF THE REIC

The calibration and use of the REIC to record dosimetric information are similar to the techniques used for EICs in general, and were discussed in Chapter 2 with regard to measurement in the saturation region of operation under the assumption that the response is independent of contamination from photo-electrons generated in the aluminum polarizing electrode. For our calibration we attempt to incorporate the effects of the polarizing electrode. If we assume linear response to irradiation and uniformity of charge on the electret surface and the electric field in the sensitive volume,
where \( Q_x \) is the charge lost from the surface of the electret during exposure-in-the-field and \( k \) is a constant of proportionality. Eq. (4.6) can be restated as:

\[
X = kA \int j \, dt,
\]

(4.7)

where \( A \) is the area of the collecting electrode and \( t \) is the time of exposure. We now substitute \( j_{\text{sat}} \) for \( j \) indicating saturation conditions:

\[
X = kA \int j_{\text{sat}} \, dt.
\]

(4.8)

Eq. (2.18) is now inserted in Eq. (4.8) to result in:

\[
X = kA \int \dot{X}(\kappa a + \lambda' \varepsilon(Z,E_\nu)(1 - e^{-3a/a_r})) \, dt,
\]

(4.9)

which accounts for charge lost due to the photo-current from the polarizing electrode. If the time derivative of Eq. (4.9) is performed, the result will be:

\[
\dot{X} = kA \dot{X}(\kappa a + \lambda' \varepsilon(Z,E_\nu))(1 - e^{-3a/a_r}).
\]

(4.10)

Evaluation of \( k \) results in:

\[
k = \left[ A(\kappa a + \lambda')\varepsilon(Z,E_\nu)(1 - e^{-3a/a_r}) \right]^{-1}.
\]

(4.11)

The value of \( k \) can be empirically determined for each chamber by evaluating...
Eq. (4.8) from experimentally determined values of $X$ and $Q_z$. The parameters seen in Eqs. (4.11) and (4.10) are defined in Section 2.8.

4.5 EFFECTS OF NON–UNIFORMITY

Until this point we have been considering the REIC system as though it were ideal, i.e. one dimensional and all phenomena were invariant under translations in the plane of the electret. It is expected however that the finite dimensions of the electrodes, will cause some variation in electric field direction throughout the chamber, making the value of charge density on the electret a function of radial position across the electret as well as the air–gap separating the opposing electrodes. This function may be affected by the presence of a spacer–ring or guard–ring.

A guard–ring is included in the construction of the REIC in an attempt to reduce the non–linear response of the REIC to radiation. Non–linear response occurs when the proportionality of Eq. (4.6) no longer holds. The guard–ring is an electrode that encircles the collector electrode. Both are covered by the electret material. The guard–ring helps to prevent the warped electric field generated at the fringe of the REIC volume from affecting the collector, thereby ensuring that ions are drawn from a constant volume of air in the REIC. As a result the measured rate of ion collection is constant for a constant exposure rate. The size of the guard–ring needed to ensure linear performance depends on the size of the air–gap $a$.

As the air–gap increases while guard–ring size remains constant, the finite dimensions of the REIC make themselves felt, despite the guard–ring, and response of the REIC to radiation grows less and less linear. The result is that the saturation current changes with exposure instead of remaining constant, and the charge is no longer a linear function of exposure. Figure 4.5 depicts the response (i.e. (a) the current and (b) the surface–charge as functions of time) of both a linear and non–linear REIC when exposed to a constant source of radiation. A constant
Figure 4.5 Comparison of non-linear to linear EIC response (a) Current versus exposure time, (b) Surface charge versus exposure time. Collector radius 19 mm, guard-ring thickness 12 mm.
current is induced in the linear REIC until almost all of the charge has been depleted from the electret. At this point the current rapidly falls from the saturation value. Current is always changing when the non-linear REIC is being discharged. A linear REIC can be transformed into a non-linear REIC by a sufficient increase in $a$ or a sufficient decrease in the size of the guard-ring. A typical ratio of air-gap to guard-ring width necessary for linear performance is 1:6.25. The relationship between guard-ring size and air-gap which allows for acceptably constant saturation currents is discussed by Ryner and Fallone et al., who also describe optimum dimensions of the REIC for dosimetry.

In Chapter 5 are presented observations of the uniformity of charge deposition on the surface of the REIC electret, and a discussion of the effect this is likely to have on the uniformity of the electric field in the REIC volume and more importantly on the non-linear response of the electret chamber to irradiation.

Chapter 6 shows our attempts to model electric fields and the REIC dynamics using an iterative computer model developed expressly for this purpose.
REFERENCES


CHAPTER 5 
EFFECTS OF APPLIED POTENTIAL & AIR–GAP

5.1 INTRODUCTION

One of the objectives of our investigation was to determine the effect of changes in applied potential \( V_0 \) and air–gap \( a \) on the uniformity of charge distribution during the charging and depletion of the radio–charged electret. The two variables, \( V_0 \) and \( a \), are important tools in the control of range and sensitivity of a REIC. Equally importantly, charge uniformity affects the linear response of the dosimeter to exposure, and one of the principal reasons for this study was to arrive at a relationship between the two. It was found that while changes in applied potential (the potential to which the electret is charged) have little or no effect on distribution, changes in air–gap radically effect the way in which charge is trapped on the electret. These changes are discussed with respect to the charging and discharging of the electret.

As was described in Chapter 3, charge distributions were obtained by non–destructively measuring surface potentials as a function of position over the electret. Charging and discharging processes, performed at a constant exposure rate of 9 R/min, were intermittently halted so that measurements could be made.

5.2 CHARGING

At this point it is useful to recall from Section 4.5 that the operation of a REIC, in which the air–gap \( a \) is large compared to the guard–ring, is characterized by non–linear response to exposure. Because of the low ratio of \( a \) to guard–ring size, the system loses its one–dimensionality and the response is no longer linear with exposure. The dynamics of a non–linear REIC may be seen in Figure 4.4 in which charging current is shown as a function of time of exposure to constant
irradiation.

Our results show that the effects of changing the applied-potential $V_o$ on the distribution of surface charge on the radio-charged electret are of a scaling nature in general. That is, the same charge "pattern" is observed when tracking the charging of an electret formed in a 4 mm air-gap chamber under 400 V as when tracking it in the same chamber but with 800 V applied. Consequently, normalized charge profiles from REIC's of differing $V_o$ are indistinguishable.

The same cannot be said of changes in air-gap. Changes in air-gap are accompanied by profound changes in the distribution of charge on the electret surface. These distributions range from concave for a small air-gap to convex for a large air-gap. At intermediate air-gaps, the charge distribution undergoes a rapid transition from concave to convex midway through the charging process.

Figure 5.1 shows charge profiles obtained at different points in the charging process for a REIC of air-gap of 2 mm and an applied potential of (a) 800 V and (b) 200 V. In these series of curves, the charge begins at a constant level of zero across the face of the dielectric. As the charging process continues, the potential at the edge rises more rapidly than does the potential in the centre of the electret. The result is a concave distribution of charge, with the concavity increasing with time of charging. For a 2 mm air-gap, the concavity (the difference between potential at the centre and the edge) never exceeds 5% of the applied potential. When, after ~25 min at $V_o = 800$ V, the edge of the electret attains the same potential as the polarizing electrode, charge deposition ceases there but continues in the centre. At this time approximately 1 mm is required to bring the potential of the centre to the same value as that of the edge.

Figure 5.2 shows corresponding curves obtained at an air-gap of 8 mm. These plots are very different from their counterparts shown in Figure 5.1. The
Figure 5.1: Charge profiles obtained at $a = 2$ mm and (a) $V_o = 800$ V, (b) $V_o = 200$ V. Exposure rate $\sim 9$ R/min. Time of irradiation in minutes marked on curves.
Figure 5.2: Charge profiles obtained at $a = 8$ mm and (a) $V_o = 800$ V, (b) $V_o = 200$ V. Exposure rate $\sim 9$ R/min. Time of irradiation in minutes marked on curves.
charge still has an initially constant value of 0 across the electret, but it is the centre which collects charge most rapidly. The result is a convex distribution with convexity increasing as the charging process continues. Eventually the progress of the central potential slows and stops, but at a value less than $V_o$. The edge potential continues to increase but very slowly. After 40 min of charging exposure with $V_o = 800$ V, there is still a significant difference between edge and central potentials, the distribution having hardly changed from the 9 min mark.

It should be noted that, between changes of $V_o$, the proper change in the Y-axis scale ($V_m$) would render the different series of charge-profiles virtually identical. This is true at least over the area of the electret observed in this investigation, and is demonstrated in Figure 5.3 Here charge profiles were obtained from an REIC of $a = 4$ mm and $V_o = 200$ V and 800 V applied. The profiles were then measured and divided by $V_o$ and are plotted as a percentage of applied potential. The two sets of curves correspond very closely.

It was decided that the "curvature" $C$ (in units of Volts) of the charge profile would be adequately represented (for present purposes) by the rather arbitrarily chosen value of the difference in mean potential measured over a central, circular area of radius $r$, and a concentric annulus of width $\Delta r$:

$$C = <V_m>_r - <V_m>_{\Delta r}$$

(14)

In our studies, $r$ was chosen to be 5 mm, and $\Delta r$ was 7.5mm — values seemingly representative of the scale over which curvature is observed. Despite the empirical nature of this definition, a plot of curvature vs. exposure time communicates a great deal about the patterns observed. Figures 5.4 and 5.5 show curvature plots for REICs charged at different $V_o$'s (shown as families of curves) and different $a$'s (shown in separate graphs, $a = 2$ and 4 mm in Figure 5.4 (a) and (b) and $a = 6$ and
Figure 5.3: Normalized charge profiles from an REIC of constant $a$ (2 mm) but $V_0 = 200$ and 800 V.
Figure 5.4: Curvature as measured during charging process for (a) $a = 2$ mm, (b) $a = 4$ mm. Exposure rate 9 R/min.
Figure 5.5: Curvature as measured during charging process for (a) $a = 6 \text{ mm}$, (b) $a = 8 \text{ mm}$. Exposure rate 9 R/min.
8 mm in Figure 5.5 (a) and (b)). For all uncharged dielectrics, $C_{t=0} = 0$, as there is no charge resident on the dielectric surface at this point. Here again, the curves from one family, i.e., curves obtained at differing $V_o$, differ from one another by a matter of scale, observable when the same curves are plotted as ratios of $C$ to $V_o$.

In contrast with the similarity between curvatures recorded for different $V_o$, those obtained when the air-gap is varied are remarkably different. Plots of $C(t)$ vary continuously through three nominal curve types as $a$ is changed. The first, for large air-gaps, can be described by a characteristically steep positive rise in initial curvature indicating a convex distribution, followed by slow decay as curvature returns to 0. The charge patterns observed when $a$ is large are similar to those seen during roller- and corona-charging. When charging an electret in an REIC of intermediate air-gap, curvature falls from 0, reaches a minimum negative value (concavity) rises past 0 to a maximum positive value, then decays to 0. For small air-gaps, the curvature grows linearly more negative, reaches a minimum, then rapidly returns to – and remains at –0 as the electret becomes fully charged.

It is well known that the air-gap of an ionization-chamber affects the sensitivity of the chamber, i.e., the current density per unit exposure, and it is not surprising that any change in current density in the REIC is reflected in a change in the rate with which the electret surface charges or discharges. This can be seen in a plot of average surface potential versus charging time in Figure 5.6. It is ironic however that, during charging, the least sensitive REIC's attain uniform charge distributions before the most sensitive chambers. The significance of this is that while REIC's of large $a$ collect charge much more rapidly during the bulk of the charging period, the final equalization period, during which charge density is rendered uniform, requires much greater exposure.

Consider the following examples. The REIC charged to 800 V in Figure 5.2 in a chamber of $a = 8$ mm has $88$ V·min$^{-1}$ added to its surface-potential when in
Figure 5.6: Plot of average surface-potential vs. charging time normalized to 1, obtained at $a = 2 \text{ mm}$ and $6 \text{ mm}$.  
saturation and is charged to a relative curvature, which is the curvature divided by $V_o$, of 2.5 % after 40 min of charging. In contrast to this, when the air-gap is reduced to 2 mm (Figure 5.1), though only 26 V·min$^{-1}$ are added to the surface, after 34 min at the same exposure rate the relative curvature is 0.008 % - 300 times less. By extrapolating the curvature curve for the 8 mm chamber, one can see that many hours of charging would be necessary to attain this type of uniformity.

It has been suggested$^2$ that the heightened sensitivity of larger air-gap REICs can be exploited without sacrificing the quick charging time of the small air-gap REIC by charging it under the latter condition and using it as a dosimeter under the former one. This could be accomplished by building the spacer ring in two parts such that a screw thread permits a telescoping action to expand the chamber after charging.

5.3 MAXIMUM CHARGE AND AIR-GAP

An interesting manifestation of the effect of the air-gap on negatively charged electrets is the plateau level achieved by $V_m$. When an electret is charged under small air-gap conditions, the highest potential (or the potential after which further increases are very slow) is equal to the applied potential $V_o$. With increasing air-gap sizes, however, this plateau becomes lower. For example, when charging an electret in a chamber of $a = 2$ mm across which 800 V are applied, $V_m$ reaches 800 V practically everywhere on the electret after 40 minutes of irradiation (roughly 320 R). If we increase the electrode separation to 8 mm and repeat the charging process, after the same exposure, though sensitivity is multiplied by a factor of 4, the potential levels off at $\sim 720$ V. In Table 5.1 is listed the maximum percentage of applied potential attained by electrets in REICs of differing $a$. Each value was obtained after charging had to all outward appearances levelled off. At very high $V_o$, the maximum $V_m$ should be slightly less than $V_o$ (as explained.
Table 5.1. Maximum percentage of applied potential obtained when charging under different conditions.

<table>
<thead>
<tr>
<th>V_o \ a</th>
<th>2 mm</th>
<th>4 mm</th>
<th>6 mm</th>
<th>8 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>98.42</td>
<td>99.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>99.61</td>
<td>97.15</td>
<td>95.00</td>
<td>91.50</td>
</tr>
<tr>
<td>400</td>
<td>99.40</td>
<td>99.30</td>
<td>93.00</td>
<td>90.30</td>
</tr>
<tr>
<td>800</td>
<td>99.60</td>
<td>99.40</td>
<td>93.80</td>
<td>90.13</td>
</tr>
</tbody>
</table>

Averages: 99.2 ± 0.6  98.9 ± 1  93.9 ± 1  90.6 ± 0.8
Section 2.6), but our highest $V_o$ is well below the 2000 V necessary\(^3\) for this to occur.

When the polarity is reversed, the dependence of plateau voltage on air-gap is greatly reduced. An experiment similar to the one discussed above was performed with a positive potential of 800 V applied to the polarizing electrode. An air-gap of 2 mm results in a $V_m$ of 95.9 ± 3.6 %, while an air-gap of 8 mm gives a $V_m$ of 93.7 ± 1.7 %. This variation is noticeably less than that observed in the prior case.

An explanation for these observations may lie in the behaviour of the photo-electrons generated at the surface of the polarizing electrode and propelled across the air-gap. If an additional (hypothetical) potential barrier on the order of eV exists just in front of the electret, ions of lower energy will be unable to cross it at some point. Photo-electrons however with energies of keV will be able to push through such a barrier, continuing the charging process. It is when the photo-electrons are in the first few millimeters of their flight that they possess sufficient energy to cross such a barrier, thus the increased charge observed for small air-gaps. An 8 mm gap exceeds the range in air (~4 mm interpolated from data published by Johns and Cunningham\(^4\)) of electrons with the most common energy, and the low-energy ions that would otherwise reach the electret are prevented from doing so by this hypothetical barrier. The measured potential of the electret surface thus differs from $V_o$ by the energy of the barrier. The origins of this barrier are unknown but may be the result of space-charge build-up in the chamber.

This would mean that in an REIC of small $a$, ions (responsible for the bulk of charge-flow) no longer contribute to the charge on the electret surface once the potential is at a certain percentage of the applied potential, but the photo-current continues to charge albeit at a much slower rate.

When positive potential is applied to the polarizing electrode, those electrons with sufficient energy to overcome the potential barrier and reach the surface of the
electret are neutralized by positive charge carriers, which would reduce the effect of photo-electrons at any air-gap, as seen in our results.

5.4 DISCHARGE

In contrast to the patterns observed during the radio-charging of an electret, the charge distribution is always convex (positive curvature) regardless of the size of the air-gap during discharge. Charge profile families from REICs of two different air-gaps are shown in Figures 5.7 and 5.8. As was noted during electret charging, applied potential determines the scaling, but the basic pattern is determined by the air-gap. When a small air-gap is present between the charged electret and the polarizing electrode, the surface defined by the potential across the electret during discharge is well approximated by a truncated cone. A central, circular, uniformly charged area of linearly descending potential is surrounded by an area across which charge drops linearly with radius. Charge is also lost from this region, but at a rate that: (a) allows the slope of this region to remain constant, and (b) is more rapid than that which applies to the central area. The result is that the flat top descends at a steady rate, but the sloped sides descend more rapidly, causing the reduction with exposure of the radius of the uniform area. This is clearly demonstrated when the REIC is discharged with an $a = 2$ mm, as shown in Figure 5.7. Larger air-gaps cause the reduction in the accuracy of the truncated-cone model making surfaces more rounded and edges less sharp as shown for an 8 mm air-gap in Figure 5.8.

The truncated cone model can be used to derive a formula for the curvature of the charge profiles as a function of time of exposure. This formula will apply as long as the size of the uniform circular area remains greater than or equal to the size of the inner circle used to calculate curvature. Because the similarity between the charge surface and a truncated cone decreases with increasing air-gap, the accuracy of the model also decreases. Consider Figure 5.9, a depiction of the truncated cone
Figure 5.7: Charge profiles obtained during discharge of REIC with $a = 2$ mm and (a) $V_o = 800$ V, (b) $V_o = 200$ V. Exposure rate $\sim 9$ R/min. Time of irradiation in minutes marked on curves.
Figure 5.8: Charge profiles obtained during discharge of REIC with \( a = 8 \) mm and (a) \( V_o = 800 \) V, (b) \( V_o = 200 \) V. Exposure rate \( \approx 9 \) R/min. Time of irradiation in minutes marked on curves.
Figure 5.9: Modelled charge-surface.
model in which \( r \) is the radius of the inner area of Eq. 5.1 and \( \Delta r \) is the thickness of the outer ring. Because of the circular symmetry of our set-up, we will work in two dimensions. The outer radius \( r' \) is stated as:

\[
r' = r + \Delta r.
\] (5.2)

The variable radius of the uniform area is represented by \( \xi \). When \( r' > \xi > r \)

\[
C = V_n - \Delta r^{-1} \int_{r}^{r'} V(r') dr',
\] (5.3)

where \( V_n \) is the nominal potential expected under linear discharge, \( \Delta r \) is the width of the annular area, \( r' \) represents radial position and is the variable of integration, and \( dr' \) is an element of length. If the potential outside \( r \) is represented as a function of \( r' \) by:

\[
V(r') = V_n - m r',
\] (5.4)

where \( m \) is the slope of the charge surface, then

\[
C = V_n - \Delta r^{-1} \int_{0}^{r'-\xi} (V_n - m r') dr' - \Delta r^{-1} \int_{r}^{\xi} V_n dr'.
\] (5.5)

The evaluation of Eq. (5.5) results in:
Since we have established that \( r' = 12.5 \text{ mm} \), Eq. (5.6) is further simplified to:

\[
C = V_n - \Delta r^{-1}(V_n(r' - m\tau^2/2) + V_n\Delta r^{-1}(\xi - r)).
\] (5.6)

We now consider an example in which the slope of the peripheral charge surface \( m = 33 \text{ V/mm} \), and \( V_n \) and \( \xi \) vary with time as follows:

\[
V_n = 800 - 25t, \quad (5.8)
\]

and

\[
\xi = 12.5 - (12.5/32^2) t^2, \quad (5.9)
\]

Eq.s (5.8) and (5.9) are good approximations to the discharge of an electret initially at 800 V in an air-gap of 2 mm with the assumption that the entire discharge time is necessary to reduce \( \xi \) to 0. Substitution of Eq.'s (5.8) and (5.9) into Eq. (5.7) results in:

\[
C = 0.000327 t^4. \quad (5.10)
\]

Figure 5.10 shows the superposition of the measured and calculated curvature plots for the conditions used in the above example. Note the close fit until the 23 minute
Figure 5.10: Measured and calculated values of curvature for the discharge of an REIC of $V_o = 800$ V and $a = 2$ mm.
mark, when the radius $\xi$ becomes smaller than $r$. At this point, the sloped banks of the charge profile converge at the centre, and $C$ rapidly descends to 0. This is readily observed in the case of 2 mm air-gaps, but becomes less apparent with larger $a$. Figures 5.11 and 5.12 show the curvature of the discharging electret for different $V_c$ and $a$. Each graph represents a different $a$ (2 and 4 mm in Figure 5.11, and 6 and 8 mm in Figure 5.12), while each curve in a graph represents a different $V_0$. Plots of $C(t)$ all possess the characteristic cusp at which they begin to fall and curve upward.

The variation of radius of the central uniform area with exposure during discharge is illustrated in Figure 5.13. The radius was determined by simply choosing the point on the charge profile where charge begins to descend rapidly—an easy task for small air-gaps resulting in smaller error bars, but more difficult as the air-gap increases.

Plotting the potential measured at the centre of the electret ($V_n$) versus exposure reveals some interesting behaviour that may be seen in Figure 5.14. The curves are linear for very small air-gaps, but as the size of the air-gap increases, linearity is lost toward the end of the discharge curve. If the non-uniform side regions alone were to affect the measured central voltage, a more rapid depletion of charge would be expected at this point, causing a steeper dive of the curve. As was observed in some cases, the depletion of charge slows with exposure, indicating the occurrence of a separate phenomenon. Sometimes however (namely $V_o = 800$ V, $a = 4, 6$ mm) this is preceded by the expected acceleration due to the encroachment of the peripheral regions. The useful range of the dosimeter can be limited by these effects far beyond what would be expected from a calculation, for a given sensitivity, of the exposure necessary to deplete the electret charge at a linear rate. For example, if an electret bears 200 nC and the REIC has a sensitivity of 50 nC/R, the chamber may not be useful for 4 R as would be suggested.
Figure 5.11: Curvatures plotted for varying $V_o$ and each $a = \cdot$ (a) 2, (b) 4 mm as a function of discharge time. Exposure rate $\sim 9$ R/min.
Figure 5.12: Curvatures plotted for varying $V_0$ and each $a = : (a) 6$ and (b) $8$ mm as a function of discharge time. Exposure rate $\sim 9$ R/min.
Figure 5.13: Estimated radius of uniform area of electret, as observed during discharge process for $a = 2$ mm.
Figure 5.14: Surface potential averaged over 1.5 mm radius central circle as a function of discharge time. (a) \( V_o = 800 \, V \), (b) \( V_o = 200 \, V \).
This effect seems closely related to the premature loss of saturation seen during charging under conditions of large $a$. In both charging and discharging calculations predict that saturation should still exist. The same explanation (as was outlined in Section 5.3) may account for both phenomena.

In an effort to determine the validity of the use of our definition of curvature, one plot of the average second derivative over spatial dimensions $x$ and $y$ was obtained and compared with curvature measurements, shown in Figure 5.15. The second derivative provides a rough estimate of radius of curvature. An image processing program provided by Noesis was used to determine the two-dimensional gradient of the charge distribution. The output of this program was then used as input and the second derivative calculated, then averaged over the area of the collector. With the allowance for a scaling factor there is good agreement between the two indicators. Since both of the above indications of curvature were of roughly equal value to us, $C$ was the standard calculated value, being easier to arrive at.

5.5 EFFECT OF GUARD-RING

The presence of a guard-ring electrode (or, more precisely, the replacement of an annulus of collector electrode by a guard-ring) has an observable effect on the distribution of charge. This effect can be seen in Figure 5.16 which shows a series of charge profiles obtained from the charging of an REIC of $a = 3$ mm, and $V_0 = 1000$ V. Because the profiles are uniform across the collector surface, it is clear that any effect of the guard-ring is confined to the guard-ring itself and when present, results in a small addition or reduction (seemingly randomly) of charge that is rarely more than 5% of the applied voltage. It is assumed that this build-up/down in charge is due to discrepancies in potential between the collector and guard due to the intercedence of the ammeter. This difference is not readily measurable in our
Figure 5.15: Comparison between calculated curvature and average second derivative of potential as a function of radius.

$V_0 = 1000 \, V$

$\alpha = 3 \, \text{mm}$

$X = 8 \, \text{R/min}$
Figure 5.16: Profiles obtained from an electret backed by collector and guard-ring.
In Chapter 6, an attempt is made to numerically predict the results of our measured charge distributions.
REFERENCES


5Visilog software, Noesis, 5bis Rue du Petit Robinson, 78350 Jouy en Josas, France.
6.1 INTRODUCTION

A numerical prediction of the distribution of surface-charge during the radio-charging and discharging of an electret was undertaken. A computer was used to solve Laplace's equation in the space of the REIC, and to thus determine the potential at discrete points within. Knowing these values, the electric field is calculated at desired points in space, and the computer-created charge is deposited on the electret surface accordingly. Laplace's equation is then re-evaluated to allow for the new boundary conditions caused by the additional charge on the electret. The solution requires knowledge of the electric field everywhere around the electret and electrodes, the manner in which charge carrying ions respond to the electric field, and the technical capacity to simulate this process. Our work was confined to two dimensions for reasons of convenience, but the circular symmetry of our experimental setup should obviate the need for three-dimensions in modelling.

6.2 PREVIOUS WORK

In the fields of Xerography and Ionography, electrets consist of photo-conductive plates bearing latent charge images backed by very large electrodes, and attempts have been made to describe the electric field generated by charge distributions on them. These calculations have been used to predict the pattern with which charged particles of toner and ink (just larger more massive ions than are used in our study) are attracted to and deposit themselves on these electrets. This process is very similar to that which occurs in the REIC during electret discharge but the backing and opposing electrodes are very large compared with the charged electret area.
The electric field lines have also been modelled\textsuperscript{4, 5} for charge distributions on a finite dielectric surface, but again the conducting substrates are assumed to be infinite, eliminating the need for perpendicular boundary conditions. In addition, this numeric formula diverges in regions close to the electret surface.

No attempt has been made in either of the techniques mentioned above to theoretically or empirically predict the nature of charging patterns on radio-charged electrets. Theoretical predictions of the patterns with which charge is depleted after the electret has been charged are confined to situations in which the electret is backed by an electrode of infinite area.

6.3 LAPLACE'S EQUATION

Laplace's Equation is traditionally expressed in differential form. It defines the function describing electric potential in a space which contains no net charge density and is surrounded by specified boundaries. In other words, given boundaries which are known, Laplace's Equation provides a means of determining the electric potential as a function of position in the space surrounded by the boundaries. The equation is stated in two dimensions:

\[
\nabla^2 V(R,z) = 0, \tag{6.1}
\]

wherein \(V\) is the potential as a function of 2–d space, \(R\) is the radial position from the centre of the electret and \(z\) is the dimension perpendicular to the electret surface.

The derivatives in this equation can be restated as the limiting values of difference equations, and then approximated by finite differences. The solution of finite difference equations is easily performed by a computer program. The solution must be true for every point in the bounded space, and so requires iterative solution
techniques. The final, generalized finite difference equation to be solved is:

\[
2/[d_1 d_2 (d_1 + d_2)] \cdot \left[ \frac{d_2 (V_1 - V_0) - d_1 (V_2 - V_0)}{(d_1 + d_2)} \right] + \\
2/[d_3 d_4 (d_3 + d_4)] \cdot \left[ \frac{d_4 (V_3 - V_0) - d_3 (V_4 - V_0)}{(d_3 + d_4)} \right] = 0.
\]

(6.2)

The values of \(V_n\) and \(d_m\) are respectively, the potential at point \(n\) and the distance between point 0 and point \(m\) (\(n = 0,1,2,3,4\) \(m = 1,2,3,4\)). These points are depicted in Figure 6.1. If all points are equally spaced, Eq. 6.2 reduces to

\[
V_1 + V_2 + V_3 + V_4 = 4V_0
\]

(6.3)

a simple statement that requires the potential at a point of interest to be the mean of the potential of its nearest neighbours.

6.4 THE CALCULATION

The use of Laplace's Equation to calculate the potential in the REIC is hampered by the lack of known boundaries at the wall of the chamber. The side walls are insulators and as such, the potential is an unknown function of position on the surface of the wall. This hurdle can be avoided by including in the calculation an additional grounded boundary around the REIC itself at a sufficient distance to minimize the effect of this boundary on the potential in the REIC. The resulting configuration is shown in Figure 6.2. The two electrodes are placed a distance \(a\) apart and are of diameter \(D\). For the present, side walls are ignored altogether, and are replaced by air. Inter-point spacing normally corresponds to 0.5 mm of real
Figure 6.1: Depiction of the spatial arrangement of points of interest in the modelling procedure.
Figure 6.2: Boundaries used in calculation of solution to Laplace's Equation.
space, but is given a value of 1 in the algorithm. To account for the thin film of dielectric, the distances $d_1$ and $d_2$ in the $z$ direction are made much smaller than the inter-point spaces in the $R$ direction for one layer of points above the collecting electrode. This is done by multiplying $d_1$ and $d_2$ by the ratio of polymer thickness $p$ to the normal spacing between lattice points $d_{\text{norm}}$. In addition, the dielectric constant of the material is allowed for by multiplying the spacing by $\varepsilon_p$, the dielectric strength of the film. The total factor by which spacing is adjusted is:

$$\varepsilon_p \cdot p / d_{\text{norm}}.$$  \hspace{1cm} (6.4)

The program used to calculate the potential as a function of position in 2-d space is listed in Appendix B as a portion of the complete electret-charging program. It permits the user to choose the relative dimensions of the electrodes, the electrode-spacing and the height and width of the outer boundary. The user then specifies the potential of all boundaries and electrodes and the number of iterations needed to accurately calculate the potential.

Figure 6.3 shows — as lines of isopotential — the results of a typical run of the program. The ratio of $a$ to $d$ was 0.04 corresponding to a 2 mm air-gap with points spaced at 1 mm intervals, the outer boundary was 10 air-gaps from each electrode in the $z$ dimension, and 0.5$d$ away in the $R$ dimension. The boundary is typically much further from the REIC during charging, but constraints on computation time made this compromise necessary. All surfaces except the polarizing electrode were held at ground, while a potential of 800 V was applied to the polarizing electrode. The program took 0.005 minutes to perform 500 iterations after which the percentage change per iteration at a point near the centre of the chamber was $1.6 \times 10^{-5}$. 
Figure 6.3: Calculated iso-potential lines for an uncharged REIC with 100 V applied to the polarizing electrode. Boundary of graph represents boundary of model, i.e. the X-ray cabinet.
6.5 CHARGE GENERATION AND DEPOSITION

One of the governing assumptions used in this model is that ionizing events occur uniformly throughout the space of the chamber. The program simulates this by sequentially "visiting" all points in the space of the chamber (directly between the electrode and electret) and creating an ionization at that point. The motion of the ion is illustrated in Figure 6.4, here the ion begins at the top right-hand corner and is moved to point O, where the surrounding points used to calculate \( E \) anew are shown and numbered 1 through 4. The electric field direction is calculated as

\[
\tan \theta = \frac{E_z}{E_r}, \tag{6.5}
\]

where \( \theta \) is the angle the electric field vector defines with the positive \( x \) axis, \( E_z \) is the component of electric field in the \( z \) direction and \( E_r \) is the component in the \( x \) direction. The electric field components are calculated as the difference between potentials of nearest neighbour points spaced in the appropriate direction:

\[
E_z = A(V_1 - V_2), \tag{6.6}
\]

\[
E_r = A(V_3 - V_4), \tag{6.7}
\]

where \( A \) is a constant of proportionality. Insertion of these expressions into Eq. (6.5) gives,

\[
\theta = \tan^{-1}\left[\frac{(V_1 - V_2)}{(V_3 - V_4)}\right]. \tag{6.8}
\]

The charge liberated from the ionizing event is moved one step in the \( z \) dimension at the angle specified above. The direction of the electric field at the new location of
Figure 6.4: Depiction of motion of charge in modelled REIC. Charge begins at the top right as shown, and is moved to a new row in the calculated direction of the electric field. E is then re-calculated using interpolated potentials from pts. 1, 2, 3 & 4 and the ion moves again, this time to point 2.
the charge (which is probably not on one of the discrete points) by interpolating to determine the potential surrounding the carrier, then re-evaluating Eq. (6.6). This is repeated until the charge reaches the same z level as the surface of the electret. If the charge lands on the electret, the potential at that point is permanently augmented by a value ΔV, if not, a new ionization is created at the next point to be visited in the chamber volume and the cycle repeated.

The program user can specify the increments by which charge is added to the electret surface, and the points (at regular intervals) in the charging process at which data are saved as output. The results from two simulated charging process are displayed as two series of charge-profiles in Figure 6.5. Figure 6.5 (a) shows the results when a is specified as 2 mm, and Figure 6.5 (b) shows the results obtained from an REIC of a = 8 mm. Superimposed on these curves in dashed lines are the corresponding measured charge profiles for comparison.

The average rate of charging is well modelled for the small air-gap as is seen in part (a) of the figure, but the concave nature of the charge-surface is lost. The numerical model generates charge-surfaces that are more uniform than their experimental counter-parts, but it predicts a small dip near the centre of the electret due to the diverging electric field.

The curvature of the charge surface is better modelled for a = 8 mm, but the non-linear response seen in the latter part of the REIC life is not predicted. We see that the modelled charge profile reaches close to the full applied potential after 9 min of charging time, but the true profile slows rapidly at 60–70% of the applied potential, 6 min after the beginning of charging.

Though the possibility exists that the reason for the relatively poor performance of the model is the choice of spatial and temporal resolution or location of outer boundary, it seems more likely that a fundamental characteristic of the REIC is not being accounted for. Perhaps the ability to calculate efficiency on a
Figure 6.5: (a) Measured and calculated charge profiles for charging of REIC of $a = 2$ mm. (b) Corresponding profiles for $a = 8$ mm. Measured curves are broken, calculated curves are solid.
local level would permit more accurate modelling. This calculation would allow the program to weight the charge generated at each point of interest by the local efficiency factor, rather than weighting the charge generated throughout the chamber for one entire time-step by the global efficiency calculated by Eq. 2.11.

Further work on the program will be directed towards accounting for both the local collection efficiency and the lower charge limit seen at higher air-gaps. The agreement in general between observed distributions and calculated leads us to believe that we are working in the right direction.
REFERENCES


CHAPTER 7
DECAY

7.1 INTRODUCTION

The success of the REIC in accurately measuring exposure to radiation is hinged on the ability of the electret to retain its charge when not being exposed. The dosimeter can still be useful if this condition is not met and decay occurs, but the rate of decay must be predictable and a time dependent calculation must be used to account for the decay of charge. To correctly determine the charge remaining on the electret after exposure in the field, the amount of charge expected to have decayed during the time between readings of \( Q_i \) and \( Q_f \) must be added to the charge actually measured by discharge or by electrostatic probing. In this chapter we present and discuss our measurements of charge decay from the radio-charged electret.

7.2 TRAPPING AND MOTION OF CHARGES

Surface charges can be stored in trapping levels located in the energy band gap between the valence and conduction bands of the polymer surface and bulk. The lack of long-range order in polymers makes for localized trapping states, holding surface charge at particular points. Experimental evidence suggests the existence of from 2 to 6 trap levels in many polymers. The energies of these levels correspond to temperatures of from 20 to 200 °C. When these temperatures are reached the respective traps are emptied. In addition, impurities and surface effects such as oxidation can increase the number of traps available for charge carriers at the surface of the dielectric.

The results of a study performed in 1979 to determine the trap levels for
Teflon FEP-A (polyfluoroethylene propylene) are shown in Table 7.1. The minimum temperature at which readily filled traps empty is 155 °C, leading one to expect a relatively stable charge distribution at room temperatures and any humanly tolerable temperatures to which an REIC might be exposed.

Once deposited on the surface of an electret, charges can be lost through recombination with charge carriers of opposite sign. Losses are either internal, in which case the source neutralizing charge is the backing electrode, or external, in which case the air above the electret is the source of neutralizing charge. In addition, the mere migration of charge away from the free surface of the electret reduces the surface potential. These processes depend on the mobility of free charge-carriers in the dielectric and the ability of trapped charges to leave their traps and become free charge-carriers, which are both partially determined by the thermal energy in the dielectric.

One commonly used model for the decay of charge from the surface and bulk of an insulating material assumes that decay is due to the injection of surface-charges into the insulator bulk where they migrate to the backing grounded electrode. In addition, thermally generated carriers contribute to the loss of these charges. This can be expressed as a loss of surface potential $V_m$ as a function of the time dependent parameter $t$:

$$V_m(t) = (1/2)e^{-\int L[t(1 - e^{-\int L})]/f}] \quad t < t_1$$

(7.1)

and

$$V_m(t) = (1/2)e^{-\int L[f/(1 - e^{-\int L})]} \quad t > t_1$$

(7.2)

where
Table 7.1 Distribution of traps for negative charges in 25 μm Teflon FEP–A

<table>
<thead>
<tr>
<th>Peak temperature (°C)</th>
<th>Physical depth (μm)</th>
<th>Kind of trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>0–25</td>
<td>Shallow, last filled</td>
</tr>
<tr>
<td>155</td>
<td>0–0.5</td>
<td>Surface trap</td>
</tr>
<tr>
<td>170</td>
<td>0.5–1.8</td>
<td>Near–surface trap</td>
</tr>
<tr>
<td>200</td>
<td>1.8–25</td>
<td>Bulk trap</td>
</tr>
</tbody>
</table>
\[ t = t' / \rho, \quad f = t_T / \tau' \]  \hspace{1cm} (7.3)

and

\[ t_T = \frac{p^2}{\mu V_0}, \quad \tau' = \frac{\varepsilon \varepsilon_0 / e \mu p_T}{\varepsilon_0} \]  \hspace{1cm} (7.4)

The quantity \( t' \) is the decay time; \( t_T \) is the transit time of the leading edge of injected charge across the thickness \( \rho \) of the electret; \( \mu \) is the mobility of these carriers; \( \tau' \) is a relaxation time characteristic of the polymer; \( p'_T \) is the thermally generated carrier concentration; and \( e \) is the elementary charge magnitude. Examples of calculated charge decay curves are shown in Figure 7.1. While these curves do not necessarily correspond to our situation (in that we know neither how conductive our materials are, nor the depth and number of traps within them), they illustrate the type of phenomena that can be anticipated.

Different techniques for extending the charge life-time on corona-charged electrets have been investigated. It has been found that heat treatment at virtually any time before, during or after charging improves stability by causing charges held in low-energy traps to move to deeper ones. Heating at moderate temperatures can be beneficial in that the most unstable traps are emptied and the remaining trapped charges are very securely held. In addition, retention times can be extended by thoroughly cleaning the electret with acetone before charging, or by placing the electret under mechanical stress. Experimental results adapted from those obtained by Anderson et al.\textsuperscript{7} for negatively corona-charged Teflon electrets are shown in Figure 7.2 (a). Differing carrier mobilities make negatively charged Teflon much more stable than its positive counterpart. Corona-charging, which was described in Chapter 2, is expected to produce electrets very similar in their charge retention properties to radio-charging because of the similarities between...
Figure 7.1: Charge decays calculated as normalized charge density versus decay time for (a) no deep trapping, but different conductivities (b) no conductivities but different degrees of trapping.
Figure 7.2: (a) Charge decay of shielded and unshielded corona–charged Teflon electrets, adapted from Anderson et al.7. (b) Charge decay of Mylar and Teflon corona–charged electrets, adapted from Sessler8.
these charging methods. In each, air ions of low energy impinge on the surface of the electret. The rate of charge loss is highly dependent on the storage conditions. An electret shielded from the atmosphere can show negligible drop after 70 days, while an unshielded electret can be reduced to 35% of its original charge in the same time (all percentage values stated in this chapter will be with respect to original surface-charge). The volume of air available to the electret when it is shielded is also important in the determination of charge-loss rates. This is so because the rate of external loss depends partly on the number of free air ions which have access to the electret surface, and the larger the volume of air to which the electret is exposed, the larger the number of ions that can deplete the net charge.

Loss measurements for electrets made of different materials are shown in Figure 7.2 (b). Though thermally charged, the decay curves of Mylar and Teflon PTFE closely resemble those obtained in our study, as will be shown in Section 7.3. An additional attractive property of Teflon PTFE is its hydrophobic nature, making it even less susceptible to external loss and independent of relative humidity. The potential for improvement of charge retention through the application of heat is demonstrated in Figure 7.3. In the study depicted, the electret is charged and heated a number of times, with the decay plotted between each cycle. Decay is accelerated by maintaining the electrets at an elevated temperature.

7.3 CHARGE DECAY RESULTS

Results from the measurement of charge decay from the faces of our electrets are quite encouraging. During the period of observation, the charged REICs were stored in a desiccating bowl, the air in which was maintained at a relative humidity of $\sim 15\%$. Measurements were made at various intervals in the decay period by removing the REICs from the bowl, dismantling them and scanning the electret in the same manner that was described in Chapter 4. After measurement, the REICs
Figure 7.3: Effects of heat treatment on charge stability of electret. (adapted from Sessler).
were reassembled and returned to the desecating bowl. The surface-potential information from each electret was averaged over the typical collector-sized area of diameter 2.5 cm. These averages are displayed in Figure 7.4 (a) as a normalized function of time.

All Teflon electrets (clean, uncleaned, 0.05 mm thick, 0.075 mm thick) achieve a state of quasi-stability after a brief period of exponential decay. This period of rapid decay lasts from 15 to 20 days after which the electret can be at 80 % (0.05 mm) or 75 % (0.075 mm) of its original charge. Presumably the level at which stability arrives depends on electret thickness. Following the rapid decay, a second period of slow, linear decay begins. This second decay may be exponential as well, but over the period of our observations a straight line fits the data very closely. An excerpt from one decay curve of a Teflon PTFE, radio-charged electret is shown in Figure 7.4 (b), where decay is typified by a decay rate of ~ 0.03 % of the original charge per day, with a linear-correlation coefficient r of 0.950. The 0.075 mm Teflon PTFE electret had been monitored for 195 days at the time of writing (the longest period of the group) and at that time possessed 70.24 % of its original charge.

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 (0.05 mm Teflon PTFE) was at 83.64 % after 117 days and the same electret but uncleaned was at 82.43 %. Both of these samples decay with a rate of approximately 0.03 % day⁻¹ as well, once stability is achieved.

Mylar (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 (with an equivalent activation energy $E_x$ of 0.18 eV) compared with Teflon PTFE ($E_x = 0.5$ eV)¹⁰. Also, the Schubweg, which is the mean distance travelled by a charge
Figure 7.4: (a) Normalized decay of different charged electrets stored in low humidity conditions. (b) Linear portion of decay of 0.075 mm, clean Teflon PTFE.
carrier before recombination, of carriers in Teflon PTFE is on the order of a factor of 6 less than in Mylar. The measured decay seems to correspond very well to the internal decay of charge from corona-charged Mylar\textsuperscript{11} (see Figure 7.2b), meaning it is probably too unstable for use in an EIC. This is especially true since there exist materials which retain their charge longer.

In addition to measuring the loss of charge from our electrets we measured the distribution of charge as well. An histogram was made of every scan performed and the spread of charge measurements about the mean on each electret was recorded. These values were recorded as standard deviations and are shown in Figure 7.5. While some redistribution of charge takes place during the initial, unstable phase, charges seem to remain in place from then on. The redistribution that occurs is somehow dependent on electret thickness.

On 25 \( \mu \text{m} \) Teflon PTFE, charges begin uniformly distributed (as is true of all electrets when charged fully) then concentrate in one area then return to a uniform distribution. This could be interpreted as an actual redistribution or as a more rapid depletion of one area followed by a catching-up by the remainder of the electret surface. This departure from uniformity occurs during the rapid decay period of the electret's life. The thicker Teflon electret undergoes a noisy loss of uniformity and remains non-uniform afterwards. This could similarly be interpreted as a decay of certain parts of the electret while the remainder stays well charged. Here again this activity takes place during that portion of the electret's life when it appears least stable.

It should be borne in mind that these electrets were all charged to the same initial potential of 200 V, and that it has been shown that higher decay rates apply to electrets charged to higher initial potentials\textsuperscript{12} due to the stronger forces to which carriers are subject as they move toward the backing electrode. Cross-over of decay curves only occurs when initially the charge layer is at a deeper location in the
Figure 7.5: Standard deviation of charge distribution over 25 mm diameter area as a function of storage time.
electret. This will not occur in the radio-charging process wherein it is expected that all charges are trapped on the surface.

In this chapter we have briefly considered a model describing the internal decay of charge from the surface of a corona-charged electret, and examined some experimental measurements of such decay. The results of decay measurements from radio-charged electrets were presented and compared to those from corona-charged electrets and found to be quite similar. Decay from negatively charged Teflon PTFE electrets is characterized by a brief period of the order of one week of rapid decay, followed by a long period of quasi-stability during which charge is lost slowly but steadily.

Such decay can easily be accounted for in the calculation of dose. Rather than simply use Eq. (2.9), one must include a term that accounts for the loss of charge due to non-irradiative causes. The new equation has the form:

\[ Q_i - Q_f - Q_{\text{dec}} \propto X, \quad (7.5) \]

where \( Q_{\text{dec}} \) is the charge expected to have been lost to decay and can be calculated if the rate of linear decay is known.
REFERENCES


CHAPTER 8
CONCLUSIONS

It seems clear that the combination of high-resolution electrostatic probe and movable 2-d platform avails itself very well to studies of the charge behaviour of an electret as produced in a radio-charged EIC. Few steps are required to ensure proper experimental conditions for the measurement of the surface charge on the electret — the major ones being that the charged surface of the electret be prevented from coming in contact with solids or liquids; and that the backing electrode be well grounded during the scanning process. The spatial sampling frequency is determined by the constraints on measurement time (though the resolution of the probe used here makes the maximum useful sampling frequency \( \sim 2 \text{ mm}^{-1} \)). The resulting data is easily handled and analysed.

We have observed in our experiments that it is possible to charge an electret in any REIC configuration \( (V_0, a) \) to a uniform state. Having said that, one should now say that while uniformity is readily achievable in smaller chambers (small \( a \)), some time is required for larger chambers to achieve the same uniformity — despite the heightened nominal sensitivity of larger chambers. It is consequently worthwhile to consider the advantages of charging in a small chamber, then replacing the chamber's spacer-ring with the one corresponding to the desired chamber sensitivity.

An indication of curvature of charge distribution is the difference between the average surface-charge of a central, circular area and a surrounding annulus on the electret. This indicator provides a qualitative understanding of the behaviour of surface charge during charging (and discharging) of the electret, and is a means of parameterizing complicated surface charge profiles, which it compliments.

Our results have demonstrated that when an electret is charged in an REIC
of small air-gap \( (a/D \approx 0.04) \) — Recall that \( D \) is the diameter of the electret), the edge of the electret charges slightly before the centre; for a large air-gap \( (a/D \approx 0.16) \), the centre is charged much more quickly; and for a medium air-gap, the charge distribution is initially concave (more intensely charged edges) but the centre catches and surpasses the edge mid-way through the charging process, producing a convex pattern. These results provide a beginning for understanding the strength of the electric-field as a function of position in the chamber, suggesting either regions of stronger field or regions on the electret which collect charge from larger volumes of air than do others.

Since the electric field strength throughout the REIC is almost always sufficient to bring about a high local collection efficiency, it seems likely that differences in the rate of charge deposition on the electret are due to differences in volumes through which the electric field sweeps over various parts of the electret, i.e. in the center, a unit area on the electret has the charge generated in a volume equal to that area multiplied by the distance between electrodes deposited onto it, while at the sides where fields bend, charge from a large volume can be deposited on a much smaller area. The result is that some areas of the electret have the charges from a very large volume deposited on them, while others are contributed to by only the areas directly between them and the polarizing electrode opposite them.

In addition to behaviour of the distribution of charge, some dependence of the magnitude of maximum charge on air-gap has been detected. This dependence is manifested as a decrease in maximum charge with increasing air-gap. It is felt that the contribution of photo-electrons from the polarizing electrode may be affected by the air-gap and cause the observed variability.

A common theme of distribution has been seen during the discharge of the electret. This pattern consists of a central, uniformly charged circular area surrounded by an annulus of linear charge gradient, forming a truncated cone. This
is similar to the way in which charged ink particles are attracted to a latent image in Xerography, where the edges of a charged area are the first to attract toner. Both the uniform and "sloped" areas are depleted linearly with exposure, but the higher decay rate of the non-uniform region causes the uniform area to decrease in size, while the sloped edge converges on the centre. When the uniform area disappears the potential over the centre of the electret drops very rapidly.

The effect of air-gap size on this behaviour is to alter the distinction between both main regions. When an electret is discharged in an REIC of large air-gap, the uniform area is less uniform, more rounded, and the slope of the peripheral area is not as straight. An added effect is that charge depletion slows before the chamber should be significantly out of the saturation region of the collection efficiency curve. As a result, the range of the REIC can be significantly hampered when high sensitivity is desired. Future work should illuminate the cause of this occurrence.

The radio-charged electret has shown that it can retain charge over long spans of time, losing it at a seemingly linear rate of 0.03 % of the original charge per day (following an initial stabilization period of 2 - 3 weeks). Over a month, this would amount to 1.2 %: a small amount that can easily be predicted and accounted for when determining the dose to the wearer of the REIC. During the settling period, some redistribution of charge seems to take place, but this can only be confirmed in future investigations. For accurate dosimetry, the REIC must also remain in conditions of saturation, thus slightly reducing the range of the dosimeter, but with proper design, the REIC can easily provide ample range.
Appendix A

Programs: *Tuscan* and *Tusurf*

*Tuscan* controls hardware that acquires data

*Tusurf* processes data.
program tvscan;
{  Scans electret in a television style with n horizontal  }
{  lines separated by diagonal fly-back lines. Data are  }
{  put in the TVSURF.DAT file where they can be copied into  }
{  any desired file.  }

uses DOS,IEEEIO,Crt;

var  ieeeout,ieeein, file1, file2: text;
response, reading, filename, name2, pos, driverpath, vold: string;
speed, dist, n, r, f: longint;
p, q, m, count, cc, sp3, g, d, yf, res: integer;
mode, gd, gm: integer;
voltage, avgz, sum, num: real;
regs: registers;

procedure checkint(signal: integer);  
{  Checks for interrupt flag  }
{  and takes appropriate action.  }
var  sp, sp2: integer;
begin
  {  Don’t know why this #.  }
  Regs.AX:=$0400;
  intr($10, regs);  
  {  Checks for flag up.  }
  While regs.ah <> 0 do begin
    writeln(ieeeout,'spoll 02');  
    {  Here 02 is being polled  }
    readln(ieeein,sp2);  
    {  to see if it actually  }
    if (sp2 and 64) = 0 then begin
      writeln(ieeeout,'non-SRQ interrupt!');  
      {  appropriate statement  }
      end;
    writeln(n);  
    {  The number of data points is printed.  }
    regs.ax:=$0000;
    n := 2000000;
    writeln(ieeeout,'Output02;K/');
  end;
end;

begin
  res := 64;
  filename := 'TVSCAN.DAT';  
  {  Data goes to file 'TVSCAN.DAT'!  }
  name2 := 'tvscan.bak';
  assign(file1, filename); reset(file1);
  assign(file2, name2); rewrite(file2);
  while not Eof(file1) do begin
    readln(file1,vold);
    writeln(file2,vold);
  end;
  close(file1);close(file2);
  rewrite(file1);
  assign(ieeeout, 'ieeeout'); rewrite(ieeeout);
  assign(ieeein, 'ieeein'); reset(ieeein);
  rawmode(ieeeout);
  rawmode(ieeein);
  IOCTL;
  writeln(ieeeout,'reset');  
  writeln(ieeeout,'fill error');
  writeln(ieeeout,'remote14');
  writeln(ieeeout,'remote02');
  writeln(ieeeout,'arm srq');  
  writeln(ieeeout,'Output14:a0clr3nt6X');  
  {  Interprets SRQ as interrupt.  }
  writeln(ieeeout,'Output02;K/');  
  writeln(ieeeout,'Output02;K/');
for n := 1 to 2000000 do begin
  checkint(10);
  writeln(ieeeout,'output02;K/');
  writeln(ieeeout,'spoll 02');
  readln(ieeein,sp3);
  writeln(ieeeout,'output02;J/');
  writeln(ieeeout,'output02;IXF4000D33750YF4000D33750/');
  writeln(ieeeout,'output02;K/');
  writeln(ieeeout, 'spoll02');
  readln(ieeein,sp3);
  writeln(ieeeout,'output02;J/');
  sum := 0;
  num := 0;
  writeln(ieeeout,'output02;IXF1000D31644YF3000D500/');
  for n := 1 to 2000000 do begin  
    num := num + 1;
    checkint(10); 
    writeln(ieeeout,'enter14'); 
    readln(ieeein,reading); 
    val(reading,voltage,cc); 
    sum := sum + voltage;
  end;
  avgz := sum / num;
  writeln('average "zero" is ',avgz);
  writeln(ieeeout,'output02;K/');
  writeln(ieeeout,'spoll 02');
  readln(ieeein,sp3);
  writeln(ieeeout,'output02;J/');
  writeln(ieeeout,'output02;IXF15822D-23770YF5109D7374/');
  for n := 1 to 2000000 do begin
    checkint(10); 
    writeln(ieeeout,'enter14'); 
    readln(ieeein,reading); 
    val(reading,voltage,cc); 
    writeln(file1,'abs(voltage-avgz) ;
    delay(24) ;
    writeln(file1,'xxxxxxxxxxxxxxx');
    writeln(ieeeout,'output02:K/');
    writeln(ieeeout, 'spoll 02');
for n := 1 to 2000000 do begin
  checkint(10);
  writeln(ieeeout,'output02;K/');
  writeln(ieeeout,'spoll 02');
  readln(ieeein,sp3);
  writeln(ieeeout,'output02;J/');
end;
writeln(ieeeout,'spoll02');
readln(ieeein,sp3);
writeln(ieeeout,'output02;J/');
writeln(ieeeout,'output02;K/<CR><LF>');
writeln(ieeeout,'output02;C/<CR><LF>');
close(ieeeout);close(ieeein);close(file1);
ieeeecomplete
uses dos;

var
  s,h,i,j,k,m,n,p,minnum,idata,z,ins,kk,res,pixmax : longint;
  w,y,r,q,data,max,maxold,uc,av,kev,time,gap,mas,rh : real;
  nunm : array[1..256] of integer;
  badln : array[0..100] of integer;
  pts,rem,dd,1, dmaxold, dmax, dminold, dmin, numless : longint;
  s:longint;
  code:integer;
  volts : array[1..300] of string[20];
  tv : array[1..300] of real;
  dummy,name, name1,name2, name3,name4, ans, ans2 : string[20];
  file1, file2, file3, file4 : text;
  month, day, year, dayofweek : word;
  hour, minute, second, sec1000: word;

begin
  name1 := 'tvscan.bak';
  name4 := 'surfpars.dat';
  if name1 = 'tvscan.bak' then writeln('WARNING - OLD VALUES');
  assign(file4,name4);rewrite(file4);
  writeln(' What would you like to call the output file? ');
  writeln(' (default is sntemp.dat ) ');
  readln(name);
  name2 := 'a:\'+name;
  name3 := 'a:\specs\' + name;
  writeln(name3);
  if name2 = '' then name2 := 'sntemp.dat';
  writeln(file4,name2);
  fdate(year, month, day, dayofweek);
  gettime(hour, minute, second, sec1000);
  writeln(' Relative humidity? ');
  readln(rh);
  writeln(' How long was irradiation? (min) ');
  readln(time);
  writeln(file4,time);
  writeln(' What energy? (kev) ');
  readln(kev);
  writeln(file4, kev);
  writeln(' What spacer? (mm) ');
  readln(gap);
  writeln(file4, gap);
  writeln(' What tube current? (mAs) ');
  readln(mas);
  writeln(file4, mas);
  writeln(file4, name2);
  res := 64;
  assign(file1,name1);reset(file1);
  assign(file2,name2);rewrite(file2);
  assign(file3,name3);rewrite(file3);
  dd:=0;
  h := 0;
  minnum := res;
  numless := 0;
  xold := 0;
  dmax := 0;
  dmin := 0;
  s := 0;
  c := 90;
  while not eof(file1) do begin
    h := h + 1;
end
else
begin
  val(volts[i], v, code);
  if abs(v) > maxold then max := abs(v);
  maxold := max;
end;
end;
c := 65536/max;
writeln(max);
writeln(file3, 'Output data stored in ', name2);
writeln('');
writeln('There are ', h, ' lines of data');
writeln(file3, 'There are ', h, ' lines of data');
writeln('');
writeln('Would you like output for Visilog (normalized to 256)');
readln(ans2);
reset(file1);
l := 0;
for m := 1 to h do begin
  for p := 1 to (num[m]) do begin
    readln(file1, volts[p]);
  end;
  d := num[m] - minnum;
  if d > dmaxold then dmax := d;
  if d < dminold then dmin := d;
  dmaxold := dmax;
  dminold := dmin;
  d := dmax;
  d := 0;
  if d >= 0 then begin
    for n := 1 to d do begin
      volts[num[m] div d + dd - num[m] div 2 div d] := 'g';
      z := num[m] div d + dd - num[m] div 2 div d;
      dd := dd + num[m] div d;
    end;
  end
else
begin
  numless := numless + 1;
  num[m] := minnum;
  for n := 1 to abs(d) do begin
    ins := abs((num[m] div d) + dd - (num[m] div 2 div d));
    dd := dd + num[m] div d;
  end;
  kk := 0;
  for n := 1 to minnum do begin
    val(volts[n-kk], tv[n], code);
    if n = ins then begin
      val(volts[n-1], a1, code);
      val(volts[n], a2, code);
      av := (a1 + a2)/2;
      tv[n] := av;
      kk := kk + 1;
    end;
  end;
end;
for n := 1 to minnum do begin
  str(tv[n], volts[n]);
end;
data := abs(data)*c/256;
end
else
begin
  data := abs(data)*100;
end;
idata := round(data);
if idata < 0 then idata:=0;
writeln(file2,idata);
s:=s+1;
pts := pts + 1;
end;
if pts < res then begin
  badln[l] := m;
l := l + 1;
end;
close(file1);close(file2);
writeln(file3,year,'/',month,'/',day);
writeln(file3,hour,':',minute,':',second);
writeln(file3,'Time =',time:5:2,'min Energy =',kev:6:1,'keV Spacer =','gap:4:1,','mm Tube Current =','mas:5:2,'mAs');
writeln(file3,'R.H. = ',rh);
writeln(' Lines with < ',res,' pts are:');
writeln(file3,' Lines with < ',res,' pts are:');
for i:= 0 to l-1 do begin
  writeln(' ',badln[i]);
  writeln(file3,','badln[i]);
  writeln(file3,'number of points in ',name2,' is ',s);
  writeln(file3,'maximum voltage is ',max*100:9:2);
  pixmax := trunc(max*c);
  writeln(file3,'maximum pixel value is ',pixmax:4);
  writeln(file3,'maximum excess is ',dmax);
  writeln(file3,'minimum excess is ',dmin);
  writeln(file3,'Number of lines with < ',res,' is ',numless);
  writeln(file3,' Number of points in ',name2,' is ',s);
  writeln(file3,' Maximum voltage is ',max*100:9:2);
  writeln(file3,' Maximum pixel value is ',pixmax:4);
  writeln(file3,' Maximum excess data is ',dmax);
  writeln(file3,' Minimum excess data is ',dmin);
  writeln(file3,' Number of lines c < ',res,' is ',numless);
  writeln(file3,'Avg in circle of rad.=10 pixels :');
  writeln(file3,'Avg in remaining ring of 15 pixels :');
  writeln(file3,'Overall average :');
  writeln(file3,'Variance of signal :');
  writeln(file3,chr(12)');
close(file3);close(file4);
Appendix B

Programs: Grow 11
Numerical modelling of REIC
program growll;
var
~~, j, m, cnt, iter, p, t, code, nprof, a, tmax, n, h, w, k : integer;
~~, c, f, isat, En, Et, conv, tcalc, E, Va, k1, k2, Vup, Vdown, Vback, Vforth, x, Dx : real;
V : array[0..80,0..120] of real;
sigma : array[5..10] of real;
name, name2, name3, name4, s, sig, ans : string;
op, op2, op3, op4 : text;
begin
name4:='test.dat';
assign(op4, name4); rewrite(op4);
writeln(' This program is designed to reproduce the ');
writeln(' charging of a radio-charged electret.' );
writeln;
writeln(' How many points across system? (0..120)');
readln(k);
writeln(' How many across the electret?');
readln(w);
conv := w/50;
writeln(' How far from top and bottom walls? (pts)');
readln(h);
writeln(' What air-gap (pts) would you like?');
readln(a);
writeln(' What voltage?');
readln(Va);
writeln(' How many iterations per time step?');
readln(iter);
writeln(' Number of time steps?');
readln(tmax);
writeln;
writeln(' How many charge profiles would you like?');
readln(nprof);
writeln(' Finally, would you like a growth curve?');
readln(ans);
writeln;
tcalc := 2.662e-8*k*(2*h+a+2)*iter*tmax;
writeln(' Program will require ',tcalc,' hours.' );
if (ans = 'y') or (ans = 'Y') then begin
  name3:='C:\curve.dat';
  assign(op3, name3); rewrite(op3);
end;
for j : = 0 to 120 do begin
  sigma[j] := 0;
end;
for t := 1 to tmax do begin
  for i := 0 to (2*h+a+2) do begin
    for j := 0 to k-1 do begin
      V[i,j] := 0;
    end;
  end;
  for j := ((k-w) div 2) to ((k-w) div 2)+w-1 do begin
    V[(h+a+1),j] := Va;
    V[h,j] := 0;
    V[h+1,j] := sigma[j];
  end;
  for cnt := 1 to iter do begin
    for i := 1 to h-1 do begin
      end;
    end;
end;
for i := h+1 to h+1 do begin
  for j := 1 to ((k-w) div 2)-1 do begin
    V[i,j+((k-w) div 2)+w-1] := \((16.38*V[i-1,j+((k-w) div 2)+w-1] + V[i+1,j + V[i,j+(k-w) div 2)+w]) /20.18;
  end;
end;
for i := h+1+a to h+1+a do begin
  for j := 1 to ((k-w) div 2)-1 do begin
    V[i,j+((k-w) div 2)+w-1] := \((V[i-1,j+((k-w) div 2)+w-1] + V[i+1,j + V[i,j+(k-w) div 2)+w]) /4;
  end;
end;
for i := h to h do begin
  for j := 1 to ((k-w) div 2)-1 do begin
    V[i,j+((k-w) div 2)+w-1] := \((1.802*V[i-1,j+((k-w) div 2)+w-1] + V[i+1,j + V[i,j+(k-w) div 2)+w]) /20.
  end;
end;
for i := h+2 to (h+a) do begin
  for j := 1 to k-2 do begin
  end;
end;
for i := (h+2+a) to (2*h+a+1) do begin
  for j := 1 to k-2 do begin
  end;
end;
if ((t) mod (tmax div nprof)) = 0 then begin
  str(t,s):
  name2:='c:\sigma'+s+'\sigma.dat';
  assign(op2,name2);rewrite(op2);
end;
for i := h to h+a+1 do begin
  writeln;
  for j := (k-w) div 2 to ((k-w) div 2)+w-1 do begin
    write(' ',V[i,j]:6:2);
  end:
end;
writeln;
writeln;
for j := (k-w) div 2 to ((k-w) div 2)+w-1 do begin
  write(' ',sigma[j]:6:2);
end;
writeln;
writeln;
{----------------------------- Charge Deposition -----------------------------}
x := x + Dx;
for n := (i-l) downto h+2 do begin
  if (round(x) >= (k-w) div 2 and (round(x) <= ((k-w) div 2)+w-1)
  Vback := V[n,trunc(x)];
  Vforth := V[n,(trunc(x)+1)];
  Vup := (x-(trunc(x)))*
    (V[(n+1),(trunc(x)+1)]-V[(n+1),trunc(x)])+V[n+1,trunc(x)]
  Vdown := (x-(trunc(x)))*
    (V[n-1,(trunc(x)-1)]-V[n-1,trunc(x)])+V[n-1,trunc(x)];
  En := (Vdown-Vup)/0.002;
  Et := -1*(Vforth-Vback)/0.002;
  E := sqrt sqr(En)+sqr(Et);
  Dx := Et/abs(En);
  x := x + Dx;
end;
end;
k1 := 1.097e-5*E/d;
k2 := 2.3903e-10*sqr(E)/sqr(d);
f := (k1 + k2)/(1 + k1 + k2);
isat := Va/(a-l)*tmax;
if (round(x) >= (k-w) div 2 and (round(x) <= ((k-w) div 2)+w-1) the
  sigma[round(x)] := sigma[round(x)] - f*isat*(En/abs(En));
end;
end;
end;
if ((t) mod (tmax div nprof)) = 0 then begin
  for j := (k-w) div 2 to ((k-w) div 2)+w-1 do begin
    writeln(op2,(V[h+l,j]-(0.31/(0.31+(a*2)))*(V[(h+l+a),j]-V[h+l,j])))
    writeln(op2,sigma[j]);
  end;
end;
if ((t) mod (tmax div nprof)) = 0 then begin
  close(op2);
end;
if (t = 1) or (t = tmax) then begin
  name:='c:\grow'+s+'.dat';
  assign(op,name);rewrite(op);
  for i:= 0 to (2*h+a+2) do begin
    for j:= 0 to (k-1) do begin
      writeln(op,i,' ',j,' ',V[i,j]);
    end;
  end;
  close(op);
end;
end;
******************************************************************************
for t := (tmax+1) to 2*tmax do begin
  for i := 0 to (2*h+a+2) do begin
    for j := 0 to k-1 do begin
      V[i,j] := 0;
    end;
  end;
  for j := ((k-w) div 2) to ((k-w) div 2)+w-1 do begin
    V[(h+a+l),j] := 0;
    V[h,j] := 0;
    V[h+1,j] := sigma[j];
  end;
  for cnt := 1 to iter do begin
    for i := 1 to h-1 do begin
      for j := 1 to k-2 do begin
        V[i,j] := ( V[i-1,j] + V[i+1,j] +
\[
V[i,j] := (16.38 \times V[i-1,j] + 1.802 \times V[i+1,j] + V[i,j+1] + V[i,j-1]) / 20.18;
\]
\[
V[i,j+(k-w) \div 2+w-1] := (16.38 \times V[i-1,j+(k-w) \div 2+w-1] + V[i+1,j+(k-w) \div 2+w-1] + V[i,j+l] + V[i,j-l]) / 20.18;
\]

\begin{verbatim}
end;
end;
for i := h+1+a to h+1+a do begin
  for j := 1 to ((k-w) div 2)-1 do begin
    V[i,j] := (V[i-1,j] + V[i+1,j] + V[i,j+1] + V[i,j-1]) / 4;
    V[i,j+(k-w) \div 2+w-1] := (V[i-1,j+(k-w) \div 2+w-1] + V[i+1,j+(k-w) \div 2+w-1] + V[i,j+l] + V[i,j-l]) / 4;
  end;
end;
for i := h to h do begin
  for j := 1 to ((k-w) div 2)-1 do begin
    V[i,j] := (1.802 \times V[i-1,j] + 16.38 \times V[i+1,j] + V[i,j+1] + V[i,j-1]) / 20.18;
    V[i,j+(k-w) \div 2+w-1] := (1.802 \times V[i-1,j+(k-w) \div 2+w-1] + V[i+1,j+(k-w) \div 2+w-1] + V[i,j+l] + V[i,j-l]) / 20.18;
  end;
end;
for i := h+2 to (h+a) do begin
  for j := 1 to k-2 do begin
    V[i,j] := (V[i-1,j] + V[i+1,j] + V[i,j+1] + V[i,j-1]) / 4;
  end;
end;
for i := (h+2+a) to (2*h+a+l) do begin
  for j := 1 to k-2 do begin
    V[i,j] := (V[i-1,j] + V[i+1,j] + V[i,j+1] + V[i,j-1]) / 4;
  end;
end;
end;
if ((t) mod (tmax \div nprof)) = 0 then begin
  str(t,s);
  name2 := 'c:\sigma'+s+'_'+dat';
  assign(op2,name2); rewrite(op2);
end;
for i := h to h+a+1 do begin
  writeln;
  for j := (k-w) \div 2 to ((k-w) \div 2)+w-1 do begin
    write(' ',V[i,j]:6:2);
  end;
  writeln;
  writeln;
  for j := (k-w) \div 2 to ((k-w) \div 2)+w-1 do begin
    write(' ',sigma[j]:6:2);
  end;
  writeln;
  writeln;
{-------------------------------- Charge Deposition --------------------------------}
d := a*0.002;
for i := h+2 to (h+a) do begin
  for j := (k-w) \div 2 to ((k-w) \div 2)+w-1 do begin
    x := 1.0*(j);
    En := (V[i-1,j]-V[i,j])/0.001;
  end;
end;
if (round(x) >= (k-w) div 2) and (round(x) <= ((k-w) div 2) + w-1)
Vback := V[n, trunc(x)];
Vforth := V[n, (trunc(x)+1)];
Vup := (x-(trunc(x)))*
(V[(n+1),(trunc(x)+1)]-V[(n+1),trunc(x)])+V[n+1,trunc(x)];
Vdown := (x-(trunc(x)))*
(V[n-1,(trunc(x)-1)]-V[n-1, trunc(x)])+V[n-1, trunc(x)];
En := (Vdown-Vup)/0.002;
Et := -1*(Vforth-Vback)/0.002;
E := sqrt(sqr(En)+sqr(Et));
Dx := Et/abs(En);
x := x + Dx;
end;
k1 := 1.097e-5*E/d;
k2 := 2.3903e-10*sqr(F)/sqr(d);
f := (k1 + k2)/(1 + k1 + k2);
isat := Va/((a-1)*tmax);
if (round(x) >= (k-w) div 2) and (round(x) <= ((k-w) div 2) + w-1) the
sigma[round(x)] := sigma[round(x)] - f*isat*(En/abs(En));
end;
end;
end;

if ((t) mod (tmax div nprof)) = 0 then begin
  for j := (k-w) div 2 to ((k-w) div 2) + w-1 do begin
    writeln(op2,(V[h+1,j]-((0.31/(0.31+(a*2)))*(V[(h+1+a),j]-V[h+1,j])))
    writeln(op2,sigma[j]);
  end;
end;

if ((t) mod (tmax div nprof)) = 0 then begin
  close(op2);
end;
if (t = 1) or (t = tmax) then begin
  name:='c:\grow'+s+'.dat';
  assign(op,name);rewrite(op);
  for i:= 0 to (2*h+a+2) do begin
    for j:= 0 to (k-1) do begin
      writeln(op,i,",",j,",",V[i,j]);
    end;
  end;
  close(op);
end;
end.

*******************************************************************************
BIBLIOGRAPHY

E.W. Anderson et al., In: Electrets, Charge Storage and Transport in Dielectrics, ed. by M.M. Perlman (Electrochemical Society, Princeton 1973).


D. Plewes and H.E. Johns, "Theoretical and experimental determination of
7, 315–323 (1980).

G. Pretzsch, "Electret charging utilizing the electret ionization chamber", Nuc. Inst.


G. Pretzsch et al, "Measurement of Tritium Activity Concentrations in Air by

L.R. Ryner, "An Electret Dosimeter Charged by Radiation Induced Ionizations in

G.M. Sessler (Ed.), Topics in Applied Physics: Volume 33: Electrets,
(Springer-Verlag, Berlin, 1980).

H. von Seggern, "Thermally stimulated decay of negatively charged Teflon–FEP",
(1979) p. 2817.