The contents of this thesis, except where indicated in the acknowledgements or by a reference, are entirely my own work.

Ken Grant
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**TABLE OF CONTENTS**

**PART A - AIR IONS AND HUMAN REACTION TIME**

**CHAPTER 1**
Introduction

**CHAPTER 2**
Natural Production of air ions

2-1 Ionization

2-2 Ionization due to Radioactivity in the Earth

2-3 Ionization due to Radioactivity in the Air

2-4 Ionization due to Cosmic Rays

2-5 Ionization due to Other Processes

2-6 Comparison of Ionizing Agents

2-7 Size and Mobility of Ions

2-8 Equilibrium of Ionization

2-9 Chemical Composition of Small Air Ions

**CHAPTER 3**
Air Ion Generators

3-1 Radioactivity

3-2 Thermionic Emission

3-3 Ultraviolet Radiation

3-4 Corona Discharge

3-5 Comparison of Corona Discharge Ion Generators
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Air Ion Measurements</td>
<td>48</td>
</tr>
<tr>
<td>4-1</td>
<td>The &quot;Blinker&quot;</td>
<td>48</td>
</tr>
<tr>
<td>4-2</td>
<td>Ion Current Probe</td>
<td>50</td>
</tr>
<tr>
<td>4-3</td>
<td>Ion Counters</td>
<td>50</td>
</tr>
<tr>
<td>4-4</td>
<td>Medion Atmospheric Ion Analyser</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>Small Air Ion Concentration</td>
<td>62</td>
</tr>
<tr>
<td>5-1</td>
<td>Outdoor Ion Concentration</td>
<td>62</td>
</tr>
<tr>
<td>5-2</td>
<td>Indoor Ion Concentration</td>
<td>66</td>
</tr>
<tr>
<td>5-3</td>
<td>Air Ion Concentrations in Canberra</td>
<td>67</td>
</tr>
<tr>
<td>5-4</td>
<td>Indoor Ion Concentration Measurements</td>
<td>69</td>
</tr>
<tr>
<td>6</td>
<td>Review of Previous Work on the Influence of Air Ions on Human Reaction Time</td>
<td>80</td>
</tr>
<tr>
<td>6-1</td>
<td>Knoll, Leonard and Highberg</td>
<td>80</td>
</tr>
<tr>
<td>6-2</td>
<td>Rheinstein</td>
<td>83</td>
</tr>
<tr>
<td>6-3</td>
<td>Halcomb and Kirk</td>
<td>87</td>
</tr>
<tr>
<td>6-4</td>
<td>Hawkins and Barker</td>
<td>90</td>
</tr>
<tr>
<td>7</td>
<td>Preliminary Experiment</td>
<td>93</td>
</tr>
<tr>
<td>7-1</td>
<td>Aim</td>
<td>93</td>
</tr>
<tr>
<td>7-2</td>
<td>Experimental Design Considerations</td>
<td>94</td>
</tr>
<tr>
<td>7-3</td>
<td>Method</td>
<td>95</td>
</tr>
</tbody>
</table>
CHAPTER 13
Mechanisms of Gallium Localization

CHAPTER 14
Scintillation Detectors
14-1 Principles of the Gamma Scintillation Counter
14-2 Gamma-ray Spectra

CHAPTER 15
Principles of the Gamma Camera
15-1 Collimators
15-2 Detector Crystal and Head Circuitry
15-3 Console Circuitry

CHAPTER 16
Optimization of Gallium-67 Images
16-1 Aim
16-2 The Gallium-67 Spectrum
   16-2-1 Method
   16-2-2 Apparatus
   16-2-3 Results
   16-2-4 Discussion
16-3 Sensitivity and Resolution
   16-3-1 Method
   16-3-2 Results
   16-3-3 Discussion
16-4 Clinical Images
<table>
<thead>
<tr>
<th>FIGURE</th>
<th>DESCRIPTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Rate of ion pair production by cosmic rays as a function of height</td>
<td>10</td>
</tr>
<tr>
<td>2-2</td>
<td>Rate of ion production over land between 1 cm and 100 cm</td>
<td>13</td>
</tr>
<tr>
<td>2-3</td>
<td>$H^+ (H_2O)_5$ reaction scheme</td>
<td>27</td>
</tr>
<tr>
<td>2-4</td>
<td>$H^+ (CH_3CN)_n (H_2O)_m$ reaction time</td>
<td>28</td>
</tr>
<tr>
<td>2-5</td>
<td>$NO_3^- (H_2O)$ reaction scheme</td>
<td>29</td>
</tr>
<tr>
<td>2-6</td>
<td>$HSO_4^- (H_2SO_4)^a (HNO_3)^b (H_2O)^c (HSO_3)^d$ reaction scheme</td>
<td>30</td>
</tr>
<tr>
<td>3-1</td>
<td>Tritium-activated ion generator</td>
<td>33</td>
</tr>
<tr>
<td>3-2</td>
<td>Small ion concentration as a function of distance from a tritium ion generator</td>
<td>33</td>
</tr>
<tr>
<td>3-3</td>
<td>Modulion negative ion generator</td>
<td>39</td>
</tr>
<tr>
<td>3-4</td>
<td>Medion negative ion generator</td>
<td>39</td>
</tr>
<tr>
<td>3-5</td>
<td>Ionotron negative ion generator</td>
<td>40</td>
</tr>
<tr>
<td>3-6</td>
<td>Kit negative ion generator and 'blinker'</td>
<td>40</td>
</tr>
<tr>
<td>3-7</td>
<td>Modulion circuit diagram</td>
<td>41</td>
</tr>
<tr>
<td>3-8</td>
<td>Kit circuit diagram</td>
<td>43</td>
</tr>
<tr>
<td>4-1</td>
<td>&quot;Blinker&quot; circuit</td>
<td>49</td>
</tr>
<tr>
<td>4-2</td>
<td>Ion current probe</td>
<td>49</td>
</tr>
<tr>
<td>4-3</td>
<td>Zeleny ion counter</td>
<td>52</td>
</tr>
<tr>
<td>4-4</td>
<td>Multiple aspiration condenser of ion counter</td>
<td>56</td>
</tr>
<tr>
<td>4-5</td>
<td>Medion Atmospheric Ion Analyser Type 134A</td>
<td>58</td>
</tr>
<tr>
<td>4-6</td>
<td>Schematic of Medion Analyser</td>
<td>58a</td>
</tr>
</tbody>
</table>
5-1  Diurnal variation of small ion concentration
5-2  Ion concentration in "normal" weather
5-3  Ion concentration in chamsin conditions
5-4  Ion concentration in (a) humid and (b) dry weather
5-5  Effect of rainfall on ion concentration
5-6  Variation of small ion concentration in a sealed room
5-7  Ion balance outdoors
5-8  Ion balance indoors
5-9  Course of ion concentration in Canberra
5-10 Course of temperature and relative humidity in Canberra
5-11 Ion concentration versus relative humidity
5-12 n⁺/n⁻ versus relative humidity
6-1  Experimental setup - Knoll, Leonard and Higheberg
6-2  Reaction time distributions - negative and positive ions
6-3  Reaction time distributions - negative ions
6-4  Reaction time distributions - positive ions
6-5  Course of reaction time over four hours
7-1  Disguised negative ion generator
7-2  Disguised ion generator circuit
7-3  Reaction timer
7-4  Reaction timer circuit
The author conducting a reaction time test 121a
Mean reaction time 129
Scan of benign gastric ulcer - see text 144
Histiocytic lymphoma (a) before, and (b) after chemotherapy 146
Normal 48 hour Ga-67 scans - see text 149
Scans of active osteomyelitis using (a) Tc-99m phosphate (b) 48 hour Ga-67 150
Synovial inflammation - see text 150
Pneumonia - 72 hour Ga-67 scan 152
Mechanism of gallium localization 157
Photomultiplier tube 162
Multi-discriminator analyser 165
Pulse stretching 166
Schematic of MCA 168
(a) Theoretical and (b) measured spectrum of nuclide with monoenergetic decay 169
Tc-99m spectrum showing iodine escape peak and lead fluorescence peak 174
Gamma camera head layout 177
Parallel hole collimator 177
Pinhole collimator 180
Converging collimator 180
Effect of distance on resolution 181
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-6</td>
<td>Effect of distance on efficiency</td>
</tr>
<tr>
<td>15-7</td>
<td>Efficiency of ½&quot; gamma camera crystal</td>
</tr>
<tr>
<td>15-8</td>
<td>Gamma camera head resistor matrix</td>
</tr>
<tr>
<td>15-9</td>
<td>Block diagram of gamma camera</td>
</tr>
<tr>
<td>16-1</td>
<td>Decay scheme of gallium-67</td>
</tr>
<tr>
<td>16-2</td>
<td>GCA-202 gamma camera taking a scan</td>
</tr>
<tr>
<td>16-3</td>
<td>Ga-67 spectrum with high energy collimator</td>
</tr>
<tr>
<td>16-4</td>
<td>Ga-67 spectrum with medium energy collimator</td>
</tr>
<tr>
<td>16-5</td>
<td>Ga-67 spectrum with low energy collimator</td>
</tr>
<tr>
<td>16-6</td>
<td>Ga-67 with absorption and scatter, high energy collimator</td>
</tr>
<tr>
<td>16-7</td>
<td>Ga-67 with scatter, high energy collimator</td>
</tr>
<tr>
<td>16-8</td>
<td>Ga-67 with absorption and scatter, medium energy collimator</td>
</tr>
<tr>
<td>16-9</td>
<td>Ga-67 with scatter, medium energy collimator</td>
</tr>
<tr>
<td>16-10</td>
<td>Ga-67 with absorption and scatter, low energy collimator</td>
</tr>
<tr>
<td>16-11</td>
<td>Ga-67 with scatter, low energy collimator</td>
</tr>
<tr>
<td>16-12</td>
<td>Spatial distribution of counts for 90 mm separation</td>
</tr>
<tr>
<td>16-13</td>
<td>Spatial distribution calibration</td>
</tr>
<tr>
<td>16-14</td>
<td>Typical spatial distribution curve</td>
</tr>
<tr>
<td>16-15</td>
<td>Ga-67 images</td>
</tr>
</tbody>
</table>
LIST OF TABLES

2-1  Comparison of ionizing agents  
3-1  Properties of α- and β-sources used in ion generators  
3-2  Power consumption and Electrode Potential of Negative Ion Generators  
3-3  Negative Ion Concentrations produced by Ion Generators  
3-4  Average ozone concentration produced by negative ion generators  
5-1  Air ion concentrations in Canberra  
5-2  Indoor ion concentration measurements  
6-1  Analysis of effects of ionization during the three eight-minute periods  
6-2  Average ion concentrations  
6-3  Mean reaction time ± standard deviation  
6-4  Between-group variation  
7-1  Reaction time results  
7-2  Ion concentration, temperature and relative humidity  
7-3  Responses to the question "Did you think that the ion generator was working today?"  
7-4  Mean reaction time  
7-5  Analysis of variance table  
8-1  Reaction time results
8-2 Environmental conditions 121
8-3 Responses to the question "Did you think your ion generator was working today?" 124
9-1 Temperature and relative humidity 125
9-2 Small ion concentration 126
9-2a Variance of reaction time distributions 128
9-3 Skewness and kurtosis of reaction time distribution curves 131
9-4 Mean reaction time 132
9-5 Analysis of variance - control vs. inactive ionizer 133
9-6 Relative difference in reaction time (%) Active ionizer vs. inactive ionizer 134
9-7 Analysis of variance - active ionizer vs. inactive ionizer 134
12-1 Estimated absorbed dose 147
14-1 Physical properties of solid scintillators 159
16-1 Isomeric transitions of gallium-67 189
16-2 Physical properties of collimators 193
16-4 Total counts in spectrum 198
16-5 Intrinsic efficiency of 12 mm NaI(Tl) crystal 205
16-6 Backscatter peaks of Ga-67 206
16-7 Spatial distribution calibration 209
16-8 Energy window settings 212
16-9 Resolution and sensitivity 212
ABSTRACT

In this thesis the results of two research projects in Medical Physics are presented. One was involved with the interaction of man with his environment and the other with the use of radionuclides in diagnosing disease. These experiments demonstrate how an understanding of the physical nature of our world may be applied to the field of medicine.

In the first project the role of air ions as part of our environment was investigated. The level of air ionization is known to vary with meteorological conditions and the factors influencing both indoor and outdoor ion concentration were studied. Surveys were conducted of air ion concentration around the Canberra district and of the concentration in one room over a two month period. The technology for artificially producing air ions, and for measuring ion concentration, was reviewed.

Air ions have been widely reported to be biologically active, with one effect being to influence reaction times. It has been shown by others that visual reaction times are decreased by the breathing of negative ions in a laboratory situation. In this project it was shown that negative air ionization also quickens reactions in a typical work situation by an average of 2.1%. This is only about a third of the improvement observed under laboratory conditions but was shown by analysis of variance that the probability of it being due to chance alone was less than one in a thousand.
The second project was concerned with the optimization of images formed with a gamma camera. This is a device to map the distribution of radionuclides in the human body as a diagnostic technique in Nuclear Medicine. One of the isotopes used for this purpose is gallium-67, the chemical properties of which make it particularly useful in the detection of tumours. However, its relatively complex spectrum has resulted in the situation where no set of imaging parameters has been universally adopted by Nuclear Medicine centres.

The clinical use of gallium-67 imaging, the generation of gamma-ray spectra and the principles of image formation with a gamma camera were reviewed. A system was developed to quantify measurements of camera sensitivity and resolution and this was used to determine the combination of collimator type and analyzer energy windows which give the optimum blend of resolution and sensitivity when imaging with gallium-67.
PART A

AIR IONS AND HUMAN REACTION TIME

Charles Coulomb in 1798 noticed that the charge on an insulated electrically charged body would leak through the air. He was thereby the first to notice the conductivity of the atmosphere, but the existence of air ions was not discovered until the work of Biever and Gaetel (1960) and (1964). These are particles of atmospheric aerosol size which have either a net positive or negative charge. The precise chemical nature of air ions is still not understood.

Air ions are formed by a variety of processes in nature and when apparatus was developed to measure ion concentration and mobility it was found that these parameters could vary widely with meteorological conditions. Furthermore, such changes seemed to correspond with changes in animal behavior. For example, preceding the arrival of the Saharan wind in the Middle East the positive ion concentration rises rapidly and some people suffer from headaches, depression and respiratory problems. Also, the particular freshness of the air near waterfalls and in pine forests has been linked with the relatively high negative ion concentrations in these regions. These and similar observations have led to speculation that negative ions have a beneficial, and positive ions a
Charles Coulomb in 1795 noticed that the charge on an insulated electrically charged body would leak through the air. He was thereby the first to notice the conductivity of the atmosphere, but the existence of air ions was not discovered until the work of Elster and Geitel (1899 a, b) and Wilson (1900). These are particles of approximately molecular size which have either a nett positive or negative charge. The precise chemical nature of air ions is still not understood.

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detrimental, influence on people but unfortunately much work on the biological activity of air ions has not been done with a sound scientific basis.

In the present project the natural production of air ions has been investigated. Factors influencing the indoor and outdoor ion concentration were studied and a survey conducted of the air ion concentration in the Canberra district. Ion generators capable of increasing the negative (or positive) ion concentration by up to a factor of ten thousand are now commercially available and the performances of a range of these were compared. The present technology for measuring ion concentration and mobility was also investigated.

The major part of this research was on the effect of negative air ions on human reaction time. A literature search revealed three previous papers on this topic. However, these experiments had design deficiencies and the results were, for one reason or another, of limited use. By recognising these inadequacies and conducting a preliminary experiment a more efficient experimental design was developed. This protocol was then used in a series of experiments to test the hypothesis that elevated levels of negative air ion concentration can decrease a person's reaction time. This was conducted in a typical work situation and it is believed that this study is the first of its kind.
CHAPTER 2:

NATURAL PRODUCTION OF AIR IONS

Section 2-1: Ionization

Ionization in the lower atmosphere is mainly due to radioactivity, both in the soil and in the air, and cosmic rays. Other, less important, processes involved the photoelectric and Lenard effects. All of these methods of ionization are discussed below.

Whatever causes the ionization, the initial result is the production of positive ions when electrons are removed from neutral molecules. The electrons, with average lifetimes of $10^{-5}$ seconds at S.T.P. become attached to other molecules, forming negative ions. Water molecules are attracted to these ions by dipole forces to form small air ions. Since the water molecule is V-shaped, with the negatively charged oxygen atom at the base of the "V" they cluster more readily around positive ions. This explains why positive ions tend to have lower mobilities than negative ions. The average lifetimes of small air ions are of the order of a hundred seconds.

If small air ions become attached to condensation nuclei large ions are formed; they have average lifetimes of about a thousand seconds.

In quantitative discussions on the ionization of the air, the standard unit of the rate of ionization is
given the symbol "I", and is defined as "one pair of ions per cubic centimetre per second" (Chalmers, 1967).

Section 2-2: Ionization due to Radioactivity in the Earth

The Earth's crust contains radioactive elements which emit α-, β- and γ- radiation into the air, causing ionization. Although the α-particles have the greatest energy their mean range is very short, and hence they can only emerge from a thin layer of soil to ionize the first few centimetres of air. Their overall effect, then, is negligible. The β-particles, however, are able to emerge from greater depths and penetrate further into the atmosphere. Also, Pierce (1958) has shown that the effects of β-particles at the Earth's surface is increasing due to radioactive fall-out. The average rate of ionization due to β-particles ranges from 1 I at the surface to 0.1 I at 10m above the surface.

The most important ionizing radiation is γ-radiation, the much longer penetration depth of which means that 1) the radiation from a greater volume of radioactive material is involved in ionization, and 2) the radiation reaches higher into the atmosphere. It has been estimated that γ-rays ionize the atmosphere at the rate of 3 I at the surface, 1.5 at 150m above it and 0.3 I at a height of 1 km.
The rate of ionization due to radioactivity in the soil varies with air currents, static stability, atmospheric pressure and, of course, proximity to radioactive rocks. Direct measurements near the ground have revealed values between 2 I and 10 I, with an average of 4 I. Since the radioactive content of seawater is very small the ionization over the oceans due to radioactivity is negligible.

Section 2-3: Ionization due to Radioactivity in the Air

Radioactive substances in the atmosphere also play an important role in the ionization. The gases radon and thoron are part of the thorium, uranium and actinium radioactive series, and emanate into the air by diffusion, thermal convection, and decreases in external air pressure. Israel (1951) measured the atmospheric content of radioactive gases, giving the results in terms of curies per millilitre. The curie (Ci) is the unit of activity, corresponding to $3.7 \times 10^{10}$ disintegrations per second. The average amount of radon in the atmosphere is $10^{-16}$ Ci/ml over land, but is only about $10^{-18}$ Ci/ml over oceans. The results for thoron were too inaccurate to give a figure, but indicate much less thoron than radon. These values for the concentration of radon fit well with its rate of exhalation from the ground, which is about $4 \times 10^{-17}$ Ci/cm². The radioactive gases are
fairly evenly distributed through the lower atmosphere by air turbulence.

In contrast to the Earth-radiation effect the majority of ionization caused by radioactivity in the air is due to α-rays; this is because there is no layer of absorbent material between the α-source and the air. The rate of ionization is calculated using the relation that if all the charges could be separated one curie would produce a current of $9.22 \times 10^{-4}$ A. This leads to the result that near the surface the ionization rate is about 4.6 I, but this falls to only 2% of this at a height of 5 km. The ionization due to atmospheric radioactivity over the oceans is negligible.

Section 2-4: Ionization due to Cosmic Rays

Cosmic rays are charged particles that bombard the Earth isotropically. When the particles first reach the Earth's atmosphere they are known as primary cosmic rays and consist of protons (90%), helium nuclei (9%), and electrons, positrons and light nuclei (total 1%). Primary cosmic rays travel at almost the speed of light and hence have remarkably high kinetic energies. The energy spectrum ranges from about $10^5$ eV for slow helium nuclei to $10^{20}$ eV for the most energetic particles. Most of the primaries however, have energies in the region of $10^{10}$ eV.
When primary cosmic rays collide with neutral air molecules they produce other high energy particles known as secondary cosmic rays. The lower energy particles are absorbed in the upper atmosphere while the higher energy particles penetrate to the Earth's surface creating a cascade of other secondary cosmic rays and ionized air molecules. These "showers" of cosmic rays may contain up to $10^8$ particles and cover an area of one kilometre diameter at the surface.

In the collision between cosmic rays and air molecules up to thirty or more $\pi$-mesons, or pions, are created, depending on the energy of the incident particle. Pions are hadrons, and may have positive or negative charge, or be electrically neutral.

The charged pions, $\pi^\pm$, of mass $139.6$ MeV, have a mean lifetime of $2.6 \times 10^{-8}$ seconds, before decaying into $\mu$-mesons (muons):

$$\pi^\pm \rightarrow \mu^\pm + \nu$$ (2.1)

Muons do not interact via the strong interaction and hence will not interact with nuclei. Also, their relatively large mass of $105.7$ MeV (c.f. mass of electron is $0.511$ MeV) means that they will not produce bremsstrahlung. As they travel down through the atmosphere, however, they lose energy by ionizing air molecules. Only about $5\%$ of the muons reach the surface of the Earth as they
have a mean lifetime of $2.2 \times 10^{-6}$ seconds, decaying according to the scheme:

$$\mu^+ \rightarrow e^+ + \nu + \nu \quad (2.2)$$

The uncharged pions, $\pi^0$, decay with a mean lifetime of $8 \times 10^{-17}$ seconds:

$$\pi^0 \rightarrow \gamma + \gamma \quad (2.3)$$

The total energy of the photons is equal to the rest mass of the pion (135.0 MeV) plus its kinetic energy. When each of the photons is in the presence of a nucleus an electron - positron pair is formed. Pair production does not occur in free space because energy and momentum cannot be simultaneously conserved under those conditions. The electrons and positrons are accelerated by the Coulomb fields of nuclei and the resulting change in kinetic energy is emitted as bremsstrahlung. The bremsstrahlung then creates more electron - positron pairs, and the process continues until the energy of the particles is below the threshold for pair production ($2m_e = 1.022$ MeV). The energy of the remaining particles is dissipated by ionizing air molecules.

In the original collision between the cosmic ray and an air molecule, high energy neutrons and protons are produced in addition to the pions discussed above.
If one of these nucleons strikes a nucleus with sufficient energy (~300 MeV), the nucleus fissions and releases protons, neutrons, deuterons, tritons and α-particles. These products of fission may cause other nuclei to undergo fission, but in any case will ionize any air molecules with which they come into contact.

The ionizing power of cosmic rays at sea-level is about 1.5 I near the equator. Ion production increases with latitude due to the Earth's magnetic field deflecting the primary cosmic rays and shielding the region of the geomagnetic equator more effectively than higher latitudes. At geomagnetic latitudes greater than 50° the rate of ionization varies with height (Fig. 2-1), with a maximum at a height of 13 km.

Section 2-5: Ionization due to Other Processes

Ionization can be produced by the photoelectric effect, in which electrons are removed from air molecules by photons with energies greater than the ionization potential of the molecule. However, solar radiation of wavelength capable of causing photoionization, that is, ultraviolet and X-radiation, will be absorbed in the upper atmosphere. Thus, although the photoelectric effect is important in ionizing the ionosphere, it is of little importance in this regard in the lower atmosphere. Lenard (1892) showed that negative ions can be produced in regions where there are water droplets in
the air, for example, near waterfalls and the sea shore. The Earth carries a net negative charge and the ionosphere a net positive charge, resulting in an electric field pointing vertically downwards with a strength of the order of 200 V/m near the surface in fine weather. This electric field polarizes the droplets, and when the droplets touch the ground they give off their positive charge to the surrounding earth. The droplets rebound when the air carries the net negative charge and when the droplets evaporate the excess charge is transferred to air molecules, so that the negative charge is known as the cloud, drift or ion formation by evaporation.

Ions may also collide with air and form corona discharge. This can only occur in ionized air if there is stormy weather, and we may say this is ionization. Metal discharge is discussed in more detail in Chapter 1.

Figure 2-1: Rate of ion pair production by cosmic rays as a function of height (after Gish, 1951)
the air, for example, near waterfalls and the sea shore. The Earth carries a nett negative charge and the ionosphere a nett positive charge, resulting in an electric field pointing vertically downwards with a strength of the order of 200 V/m near the surface in fine weather. This electric field polarises the droplets, and when the droplets touch the ground they give off their positive charge to the negative Earth. The droplets rebound into the air carrying nett negative charge and when the droplets evaporate the charge is transferred to air molecules, so forming negative ions. This process is known as the Lenard effect or ion formation by evaporation.

Ionization by collision occurs in the phenomena of lightning flashes and point, or corona, discharge. This can only occur in localised regions in stormy weather, and so causes no appreciable nett ionization. Point discharge is discussed in more detail in Chapter 3.

Section 2-6: Comparison of Ionizing Agents

In Table 2-1 the rates of ionization due to the principal ionizing agents are summarized. The values given are averages and refer to measurements taken at a height of one metre. Note that ionization due to radioactivity can vary widely depending on geographical location and weather conditions and ionization due to cosmic rays varies slightly with latitude.
TABLE 2-1 Comparison of Ionizing Agents

<table>
<thead>
<tr>
<th>IONIZING AGENT</th>
<th>RATE OF IONIZATION (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Over Land</td>
</tr>
<tr>
<td>Radioactivity in Soil</td>
<td>4.0</td>
</tr>
<tr>
<td>Radioactivity in Air</td>
<td>4.6</td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td>1.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Below one metre the relative importance of the ionizing agents are different because of the effects of α- and β-particle emitters on and just below the surface. The variation with height of the rate of ionization is shown in Figure 2-2.

Section 2-7: Size and Mobility of Ions

There are two main classifications of ions, viz. "small" and "large". Small ions are defined as those having mobilities between 1 and 2 cm/sec in an electric field of strength 1 V/cm at S.T.P. Large ions have mobilities in the range between $3 \times 10^{-4}$ and $8 \times 10^{-3}$ cm/sec/V/cm.

The mobility of small ions is influenced by air pressure, humidity, the age of the ions and the presence
Figure 2-2: Rate of ion production over land between 1 cm and 100 cm (from Smith, 1958)
of impurities. Furthermore, if all of these factors are the same negative ions have greater mobilities than positive ions. This indicates that small ions have a structure which is more complex than just single molecules which have gained or lost electrons. Research has shown that a small ion consists of several neutral gas or water molecules attached to an ionized molecule by dipole and van der Waals forces. The composition of these ions is discussed in Section 2-9.

Large ions discovered by Langevin in 1905, are charged condensation (Aitken) nuclei. These nuclei are minute particles of salt, dust and combustion products, and have radii of the order of $10^{-7}$ m. They are the sites of water condensation when the air becomes saturated with moisture. Large ions are more abundant in urban than rural areas.

The physical difference between small and large ions is more than just that of mobility. If a large ion loses its charge it continues to exist as a neutral condensation nucleus. However, when a small ion becomes electrically neutral the molecules of which it is comprised are no longer attracted and the structure ceases to exist. Also, it is believed that small ions are biologically more active than large ions, possibly because they can more easily penetrate into the alveoli of the lungs.

A group of ions has been discovered with mobilities between those of the two main classifications, known
as intermediate ions. However, the results of research in this area have been somewhat contradictory. Some workers found that air ions have mobilities which can be divided into distinct groups while others found a continuum of mobilities. Pollock (1915) claimed that intermediate ions could only exist at low humidity but Wait (1935 b) and Hogg (1939) found no such effect. Hogg postulated that intermediate ions consist of particles of sulphuric acid, and if this substance is necessary for the formation of intermediate ions it may help to explain some of the discrepancies.

Section 2-8: Equilibrium of Ionization

In a given volume of air under steady-state conditions the number of ions of each species is constant. That is, for each distinct size of ion and for ions of both signs the number of ions entering the volume plus the number created in the volume equal the number leaving the volume plus the number destroyed in the volume. Since in fine weather the number of ions of each kind entering a volume will equal the number leaving this aspect can be ignored. This is not the case close to the surface, however, because of the rapid variation with height of the rate of ionization.

There are three mechanisms for the destruction of small air ions: 1) When small ions of opposite sign
recombine they form neutral molecules. 2) When a small ion combines with a large ion of opposite sign, a neutral condensation nucleus and neutral molecules are formed. 3) When a small ion combines with a nucleus, a large ion is formed. In addition to this, large ions are destroyed when ions of opposite signs combine, forming nuclei. The rate of combination of ions is proportional to the number per unit volume of the types of ions involved, and a combination coefficient can be defined for each of the processes outlined above.

In the following treatment it is assumed that multiply-charged ions are not formed and that large ions are of the same size. Also, the possible effects of intermediate ions are not considered.

Define:  
\[ n_1 = \text{number of small positive ions per unit volume} \]
\[ n_2 = \text{number of small negative ions per unit volume} \]
\[ e_1 = \text{charge on small positive ions} \]
\[ e_2 = \text{charge on small negative ions} \]
\[ w_1 = \text{mobility of small positive ions} \]
\[ w_2 = \text{mobility of small negative ions} \]
\[ N_0 = \text{number of neutral nuclei per unit volume} \]
\[ N_1 = \text{number of large positive ions per unit volume} \]
\[ N_2 = \text{number of large negative ions per unit volume} \]
\[ z = N_0 + N_1 + N_2 \]
\[ q = \text{rate of production of small ions} \]
\[ \alpha = \text{combination coefficient between small ions of opposite sign} \]
\[ \eta_{12} = \text{combination coefficient between small positive ions and large negative ions} \]
\[ \eta_{21} = \text{combination coefficient between small negative ions and large positive ions} \]
\[ \eta_{10} = \text{combination coefficient between small positive ions and neutral nuclei} \]
\[ \eta_{20} = \text{combination coefficient between small negative ions and neutral nuclei} \]
\[ \gamma = \text{combination coefficient between large ions of opposite sign} \]

For small ions:

\[
\frac{dn_1}{dt} = q - \alpha n_1 n_2 - \eta_{12} n_1 N_2 - \eta_{10} n_1 N_0 \quad (2.4)
\]

\[
\frac{dn_2}{dt} = q - \alpha n_1 n_2 - \eta_{21} n_2 N_1 - \eta_{20} n_2 N_0 \quad (2.5)
\]

Now, \( n_1 \ll N_1 \) and \( n_2 \ll N_2 \) so that the term \( \alpha n_1 n_2 \) can be neglected. Also, at equilibrium

\[
\frac{dn_1}{dt} = \frac{dn_2}{dt} = 0
\]
\[ \therefore (2.4) \Rightarrow 0 = q - \eta_{12} n_1 N_2 - \eta_{10} n_1 N_0 \]
\[ q = \eta_{12} n_1 N_2 + \eta_{10} n_1 N_0 \tag{2.6} \]

and \((2.5) \Rightarrow 0 = q - \eta_{21} n_2 N_1 - \eta_{20} n_2 N_0 \)
\[ q = \eta_{21} n_2 N_1 + \eta_{20} n_2 N_0 \tag{2.7} \]

Combining \((2.6)\) and \((2.7)\):
\[ \eta_{12} n_1 N_2 + \eta_{10} n_1 N_0 = \eta_{21} n_2 N_1 + \eta_{20} n_2 N_0 \tag{2.8} \]

Similarly, for large ions:
\[ \frac{dN_1}{dt} = \eta_{10} n_1 N_0 - \eta_{21} n_2 N_1 - \gamma N_1 N_2 \tag{2.9} \]
\[ \frac{dN_2}{dt} = \eta_{20} n_2 N_0 - \eta_{12} n_1 N_2 - \gamma N_1 N_2 \tag{2.10} \]

Since \(\gamma << \eta_{12,21}\) (where \(\lambda = 1, 2; m = 0, 1, 2\)) the term \(\gamma N_1 N_2\) is negligible. Again, at equilibrium:
\[ \frac{dN_1}{dt} = \frac{dN_2}{dt} = 0 \]
\[ (2.9) \Rightarrow 0 = \eta_{10} n_1 N_0 - \eta_{21} n_2 N_1 \]
\[ \eta_{10} n_1 N_0 = \eta_{21} n_2 N_1 \tag{2.11} \]
Equations (2.8), (2.11) and (2.12) were first derived by Nolan and de Sachy (1927). Usually the number of large positive ions and the number of large negative ions are equal, so we can define \( N = N_1 = N_2 \). Then

\[
(2.11) \Rightarrow \quad \eta_{10} n_1 N_0 = \eta_{21} n_2 N
\]

(2.12) \Rightarrow \quad \eta_{20} n_2 N_0 = \eta_{12} n_1 N

(2.13) \times (2.14): \quad \eta_{10} \eta_{20} n_1 n_2 N_0^2 = \eta_{12} \eta_{21} n_1 n_2 N^2

\[
N^2 = \frac{\eta_{10} \eta_{20}}{\eta_{12} \eta_{21}} N_0^2
\]

\[
\frac{N}{N_0} = \left( \frac{\eta_{10} \eta_{20}}{\eta_{12} \eta_{21}} \right)^{1/2}
\]

Similarly, division of equation (2.13) by (2.14) yields the result:

\[
\frac{n_1}{n_2} = \left( \frac{\eta_{21} \eta_{20}}{\eta_{12} \eta_{10}} \right)^{1/2}
\]

If the combination coefficients involving large
ions and nuclei are constant then the ratio of positive to negative small air ions will also be constant. By measuring this ratio for a volume of air in ionization equilibrium it is possible to tell whether or not the combination coefficients are in fact constant. Any variation in the coefficients is a consequence of changes in the physical state of the large ions.

Under some circumstances the differences between the combination coefficients of positive and negative small ions can be ignored. Equations (2.6) and (2.12) then simplify to:

\[ q = \eta_n N + \eta_0 n N_0 \] 

(2.17)

and \[ n N = \eta_0 N \] 

(2.18)

Nolan and de Sachy (1927) made the assumption that the tendency for small ions to combine with oppositely charged large ions rather than with condensation nuclei is independent of sign. That is, the ratios \( \eta_{21}/\eta_{20} \) and \( \eta_{12}/\eta_{10} \) are equal. They further assumed that the number of combinations between small ions and nuclei due to polarization of nuclei was negligible compared to those due to chance collisions of the particles. This implies that differences between \( \eta_{10} \) and \( \eta_{20} \) are a result of variance between the speeds, and hence mobilities, of the small ions. This theory predicts
that $n_{20}/n_{10} = w_2/w_1$ whereas experiments suggest that $n_{20}/n_{10} = (w_2/w_1)^{3/4}$; there is no theory to adequately explain this.

Based on the above assumptions, Gish (1939) derived the result:

\[ q = \alpha' n^2 + \beta' n N \]  

(2.19)

where \( \alpha' = \frac{\alpha n_{10}}{n_{20}} \)

\[ \beta' = \frac{2 \eta_{12}}{2 + \eta_{12}/\eta_{10}} \]

Substituting for the experimentally-determined values of the \( n \)'s, Gish found that for Washington \( q \) was between 14 and 18 I, whereas the results from direct measurements were from 6 to 8 I.

Whipple (1933), like Nolan and de Sachy, assumed that combinations of small ions and nuclei are mainly due to accidental encounters, but he reasoned that in the case of small and large ions there would be extra collisions because of electrostatic attraction. Based on this, he found the differences between the relevant combination coefficients to be given by:

\[ \eta_{12} - \eta_{10} = \frac{e_1 w_1}{\varepsilon_0} \]  

(2.20)

\[ \eta_{21} - \eta_{20} = \frac{e_2 w_2}{\varepsilon_0} \]  

(2.21)
where \( \varepsilon_0 \) is the permittivity of free space.

Now, (2.6) \[ q = \eta_{12} n_1 N_2 + \eta_{10} n_1 N_0 \]

\[ = \eta_{12} n_1 N + \eta_{21} n_2 N \quad \text{from (2.11)} \]

\[ q/N = \eta_{12} n_1 + \eta_{21} n_2 \quad (2.22) \]

and (2.7) \[ q = \eta_{21} n_2 N_1 + \eta_{20} n_2 N_0 \]

\[ = \eta_{10} n_1 N_0 + \eta_{20} n_2 N_0 \quad \text{from (2.11)} \]

\[ \therefore \quad q/N_0 = \eta_{10} n_1 + \eta_{20} n_2 \quad (2.23) \]

(2.22) - (2.23):

\[ q/N - q/N_0 = \eta_{12} n_1 + \eta_{21} n_2 - \eta_{10} n_1 - \eta_{20} n_2 \]

\[ q(1/N - 1/N_0) = n_1(\eta_{12} - \eta_{10}) + n_2(\eta_{21} - \eta_{20}) \]

\[ q \frac{N_0 - N}{N N_0} = n_1 \frac{e_1 w_1}{\varepsilon_0} + n_2 \frac{e_2 w_2}{\varepsilon_0} \]

\[ q = \frac{N N_0}{N_0 - N} \frac{1}{\varepsilon_0} (n_1 e_1 w_1 + n_2 e_2 w_2) \]

\[ = \frac{N_0}{\varepsilon_0} \frac{n_1 e_1 w_1 + n_2 e_2 w_2}{N_0/N - 1} \quad (2.24) \]
Wait (1935a) substituted the relevant values for Washington into (2.24) and obtained a rate of small ion production of 4.5 I.

It is seen that neither of the theories outlined above give rise to values of $q$ in agreement with direct measurement. This is probably due to the fact that the former are based on measurements which assume a state of equilibrium, which is not the case.

The rate of approach to equilibrium can be estimated under conditions such that the differences between ions of each sign can be neglected. Then

\[
\frac{dn}{dt} = q - \alpha n^2 - \eta nN - n_0 nN_0 \quad (2.25)
\]

This can be integrated to give

\[
n = \sqrt{\frac{\delta}{\alpha}} \frac{e^{2/\alpha \delta t} - 1}{e^{2/\alpha \delta t} + 1} \quad (2.26)
\]

where \( \gamma = \eta N + n_0 N_0 \)

\[
\delta = q + \frac{\gamma^2}{4\alpha}
\]

Substitution of typical values for the various parameters shows that it approaches its final value with a half-value time of the order of one second. Also,

\[
\frac{dN}{dt} = n_0 nN_0 - n nN \quad (2.27)
\]
If it is assumed that the concentration of small ions has essentially reached equilibrium, and that the sum of nuclei and large ions is constant, i.e. \( Z = N_0 + 2N \) is constant, then (2.27) yields on integration

\[
N = \frac{Z \eta_0}{2\eta_0 + n} + e^{-(2\eta_0 + \eta) n t}
\]  \hspace{1cm} (2.28)

When measured values of the parameters are inserted into this equation, it is found that \( N \) has a half-value time of around ten minutes. This is much longer than the corresponding time for small ions, and means that in free air conditions would usually not be steady enough to allow the large ion concentration to reach equilibrium.

In equation (2.4) the term in \( a \) can often be neglected, giving

\[
\frac{dn_1}{dt} = q - \eta_{12} n_1 N_2 - \eta_{10} n_1 N_0
\]

\[
= q - \beta n_1
\]  \hspace{1cm} (2.29)

where \( \beta = \eta_{12} N_2 + \eta_{10} N_0 \) is called the "dissipation coefficient". From (2.29) it is apparent that \( \beta n_1 \) is the rate of destruction of small positive ions, and hence that \( \beta^{-1} \) is the average life of such an ion. Under conditions of small ion equilibrium \( q = \beta n_1 \) and \( \beta \) can be calculated from measured values of \( q \) and \( n_1 \).
If the average value of $q$ over land is taken as 11 I, then in regions of low pollution $n_1 = 550 \text{ ml}^{-1}$ and $\beta^{-1} = 50$ seconds. However, in cities and industrial regions $n_1$ might be only 200 $\text{ ml}^{-1}$, giving an average small ion lifetime of 20 seconds or less.

Section 2-9: Chemical Composition of Small Air Ions

The identity of air ions at sea level has not yet been fully determined. This is because the low ion concentrations and difficulty in handling large ions with very small binding energies has not allowed direct mass analyses of the ions (Elford, 1982).

The most promising technique to date is to analyze air ions 15 to 60 km above sea level by rocket-borne mass spectrometers and extrapolate these results. This is possible because the relative abundances of the neutral atmospheric components are constant up to a height of about 70 km. Water vapour concentration does vary with height but this only effects the degree and rate of ion clustering and not the basic reaction scheme.

In Elford's summary of research in this area he concludes that the dominant positive air ions at sea level are $H^+(H_2O)_5$, $H^+(H_2O)_6$ and $H^+(\text{CH}_3\text{CN})_n(H_2O)_m$ where $n = 1, 2, 3$ and $m = 1, \ldots, 6$. The reaction schemes are shown in Figures 2-3 and 2-4. There should be at least twenty species of negative ions at sea level.
of general form

\[ \text{HSO}_4^- \quad (\text{H}_2\text{SO}_4)_a \quad (\text{HNO}_3)_b \quad (\text{H}_2\text{O})_c \quad (\text{HSO}_3)_d \]

where \( a = 1, \ldots, 7 \), \( b = 1, 2, 3 \), \( c = 1, 2, 3 \) and \( d = 1, \ldots, 7 \).

Figures 2-5 and 2-6 show the reaction scheme by which the constituent ions of this cluster are formed.
Figure 2-3: H⁺(H₂O)₅ reaction scheme
FIGURE 2-4 $H^+(CH_3CN)_n(H_2O)_m$ reaction scheme
FIGURE 2-5  NO$_3^-$($H_2O$) reaction scheme
FIGURE 2-6

reaction scheme
CHAPTER 3:

AIR ION GENERATORS

The natural concentration of air ions, as discussed in the previous chapter, is subject to considerable fluctuations. To make the results of biological experiments involving air ions meaningful the ion concentration must be constant, reproducible, and usually raised to levels well above the ambient concentration. Ion generators, using various physical processes, have been developed to meet these conditions and are described below:

Section 3-1: Radioactivity

Ionization of the air occurs in Nature mainly due to the action of γ-rays (Section 2-2). In an artificial ion generator using radiation, however, shorter range radiation is desirable in order to minimise the health risk. Consequently α- and β-ray sources are used and the properties of the more commonly used sources are listed in Table 3-1.

Table 3-1: Properties of α- and β-sources used in ion generators

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Type of Decay</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>β</td>
<td>12.2 yr</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>β</td>
<td>10.4 yr</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>β</td>
<td>21 yr</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>α</td>
<td>138.4 days</td>
</tr>
</tbody>
</table>
An ion generator using a tritium ($^3\text{H}$) source developed by the Wesix Corporation is shown in Figure 3-1. The source consists of about 1.9 MBq of tritium gas absorbed in a zirconium foil disk of 7mm diameter. This foil is mounted on a 50mm aluminium bias electrode, but they are separated by an electrical insulator. A plastic shield surrounds the assembly to protect the user.

Tritium decays by $\beta^-$-decay, releasing $\beta^-$-particles of maximum energy 18 keV and average energy 3 keV. Each of the $\beta^-$-particles, by ionizing air molecules, releases about 100 free electrons on the average. These attach themselves to neutral molecules within $10^{-6}$ seconds and hence equal numbers of positive and negative ions are formed. In the absence of an applied electric field the ions would recombine resulting in no nett ionization. To prevent this a voltage of 1 kV is applied to the bias electrode, with the polarity of the new voltage corresponding to the sign of ions that are desired. An ion generator with these dimensions would have an ion current of about $10^{-9}$A. Figure 3-2 shows a graph of ion concentration versus distance from a tritium ion generator.

An ion generator using the $\alpha$-particle source Po-210 would be more efficient as each $\alpha$-particle could produce about 150,000 ion pairs. However, its short half-life of 138.4 days makes it inconvenient and it...
Figure 3-1: Tritium-activated ion generator

Figure 3-2: Small ion concentration as a function of distance from a tritium ion generator.
is rarely used. Pb-210 with a half-life of 21 years would be more suitable, but it also emits $\gamma$-radiation, making it necessary to provide special shielding.

Krypton-85 has been successfully used in an ion generator by the U.S. Radium Company. In this generator the Kr-85 gas is sealed in a small tube, and an activity of 1.7 MBq produces an ion current of $10^{-8}$ A.

Section 3-2: Thermionic Emission

Metals and some other substances at high temperatures emit electrons, the number depending on the temperature and thermionic characteristics. The electric current density is given by

$$ j = AT^2 e^{- \phi/kT} $$

(3.1)

where $A$ is a constant dependent on the material, $T$ is the absolute temperature, $\phi$ is the work function of the material and $k$ is Boltzmann's constant.

The number of electrons emitted by common heating elements such as platinum or nichrome would be low but by coating the element with a material of low work function such as barium oxide the number of ions emitted would be greatly increased. Martin (1952) has shown that as a result of impurities striking the element positive ions are also produced.

Work done by Dessauer involved a modified version of this thermionic ion generator. A block of purified
and compressed magnesium oxide was heated by a platinum filament to a temperature of 1200°C. Air was blown over the block and a large number of particles of MgO were dislodged to gain negative charge from the thermionically released electrons. Charge separation effects were also probably involved, and positive ions were removed by an applied electric field. Ion concentrations of the order of $10^7$ ions/ml were obtainable by this method, but a high proportion of these would be large ions.

Section 3-3: Ultraviolet Radiation

Air molecules are not ionized directly by even the shortest - wavelength UV-radiation ($\sim 185$ nm), but UV lamps are still able to ionize the air. This is due to the photoelectric effect where electrons are ejected from nearby metals being irradiated. The maximum kinetic energy of photoelectrons is given by Einstein's photoelectric equation:

$$E_{\text{max}} = h\nu - \phi \quad (3.2)$$

where $\nu$ is the frequency of the incident radiation, $h$ is Boltzmann's constant and $\phi$ is the work function of the metal.

It is desirable to use the longest wavelength radiation possible i.e. use metals with small work
functions, because UV radiation of wavelength less than 200 nm produces ozone by the dissociation of oxygen.

Only negative ions are produced by UV radiation since only electrons will be ejected from the metal surfaces. The electron affinity of oxygen molecules is greater than that of nitrogen, so a preponderance of negative oxygen ions is produced. These ions would then tend to be attached to dirt particles by polarization, creating large ions. The ratio of small to large ions would depend on the concentration and type of dust in the air.

Section 3-4: Corona Discharge

The vast majority of air ion generators now use the phenomenon of corona (or point) discharge. In this type of generator a large d.c. potential is applied to a wire of very small diameter (~ 50 µm) or, more commonly, to a bank of four or five needle points. The latter is favoured because it produces a stronger electric field for a given applied potential. (See, for example, Jackson 1975). The magnitude of the applied potential is usually of the order of a few kilovolts with the polarity depending on whether negative or positive ions are to be produced. At such high voltage ozone and nitric oxides can also be produced but the concentration of these undesired
by-products can be kept to an acceptable level by proper
design of the generators.

The actual ionization involves collisions between
electrons and air molecules. There will always be some
electrons in the air released by cosmic rays or radioactivity
ionizing air molecules, and these are accelerated by the
strong electric field near the points. The electrons will
acquire kinetic energy of \( KE = eV \), where \( e \) is the electronic
charge and \( V \) is the potential difference through which it is
accelerated, and if this is greater than the ionization
potential of a molecule with which it collides, an electron
will be removed from it. This electron will also be
accelerated by the electric field and the process continues,
greatly increasing the positive ion concentration. In a
positive ion generator, the needles have a positive potential
which collects the free electrons and repels the positive ions.
Conversely, in a negative ion generator, the needles have a
negative potential which collects the positive ions and repels
the electrons, which then attach themselves to neutral
molecules to form negative ions.

Corona discharge also occurs naturally under some
weather conditions. The Earth's electric field lines
tend to be perpendicular to the surface but if a pointed
conductor was set up on the surface field lines would
be deflected towards it, increasing the magnitude of
the field. Trees often serve in this role and when a
sufficiently high field strength is obtained ionization
by collision occurs as described above. This effect is more prominent in stormy weather when the magnitude of the local electric field is increased severalfold.

Section 3-5: Comparison of Corona Discharge Ion Generators

Three commercial corona discharge-type ionizers, viz. the "Ionotron", "Medion" and "Modulion" units, and an ionizer built by the author, were available for comparison. The circuits of these were examined and a comparative study of their ionizing power, ozone production and power consumption was conducted.

The Modulion ionizer and its circuit diagram are shown in Figures 3-3 and 3-7 respectively. In this model the 240 volt mains supply is fed into the primary of a transformer with a voltage step-up of 5:1. The secondary voltage is used as the input of a four-stage Cockcroft-Walton voltage multiplier, in which the output of each of four successive half-wave rectifiers is connected in series with the previous one. The orientation of the diodes determines the polarity of the output voltage, and in this case a negative voltage is produced. A 100 MΩ resistor in series between the voltage multiplier and the four ionizing electrodes ensures that the output short-circuit current is only of the order of 100 µA.
FIGURE 3-3: Modulion negative ion generator

FIGURE 3-4: Medion negative ion generator
FIGURE 3-5: Ionotron negative ion generator

FIGURE 3-6: Kit negative ion generator and "blinker"
Figure 3-7: Modulation negative ion generator circuit
The Medion and Ionotron ionizers, shown in Figures 3-4 and 3-5, have circuits which are similar to that of the Modulion. However, the Ionotron model has two additional features. Firstly, the output voltage is adjustable to vary the rate of ionization, and secondly it has an electric fan which the manufacturers claim gives a more directional flow of ions.

The fourth ionizer involved in this study was built by the author according to a design published in Electronics Today International, April 1981. The completed ionizer is shown in Figure 3-6, and its circuit diagram is shown in Figure 3-8. This ionizer differs from the commercial ones in that it does not operate directly from the mains supply, but instead is designed for an input voltage of 9 to 14 V d.c. The reason for this was that this would be less hazardous should the builder experiment with the design.

The circuit can be divided into two main sections: a dc-to-ac inverter and a voltage multiplier-rectifier. The inverter consists of a 555 timer (IC1) arranged as an astable multivibrator oscillating at approximately 25 kHz. The output of IC1 is used to drive transistors Q1 and Q2, and a trimpot in one of the timing inputs of IC1 allows adjustment of the mark-to-space ratio of the output to ensure equal drive to Q1 and Q2. Since both Q1 and Q2 are npn-type transistors, transistor Q3 is necessary to invert the drive to Q2 so that
Figure 3-8: Kit negative ion generator circuit
it will be off when Q1 is on, and vice versa. These alternately switch current through the primary of transformer T1, which provides a voltage step-up of 25:1. The voltage multiplier-rectifier is simply a six-stage Cockcroft-Walton voltage multiplier, similar to those in the commercial ionizers.

The designer claims that Q1 and Q2 do not require heatsinks, but it was found that in operation they became very hot. Using heatsinks did not solve the problem, and the reason for this overheating is probably because transistors Q1 and Q2 are not switching quickly enough and hence are spending too much time in the active region of operation, where most heat is generated.

The supply current and voltage of each of the ionizers was measured, and the power consumption calculated. The potential of the electrodes was measured with an electrostatic voltmeter, and these results are given in Table 3-2. For the Ionotron negative ion generator, these measurements were repeated for all combinations of maximum and minimum electrode potential and with the fan switched on and off.

Using the Medion Atmospheric Ion Analyser described in Section 4-4, the ion concentration produced by each of the ion generators was measured at three distances from the generators. This was done in a room of dimensions 4.0 m x 2.5 m x 3.0 m \((30\text{m}^3)\) which contained no other electrical apparatus. The negative ion concentration
was allowed to fall to its ambient level between measurements.

Table 3-2: Power Consumption and Electrode Potential of Negative Ion Generators

<table>
<thead>
<tr>
<th>Ion Generator</th>
<th>Current (mA)</th>
<th>Power (W)</th>
<th>Electrode Potential (-V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kit 500</td>
<td>500 (6.1 Vdc)</td>
<td>3.1</td>
<td>3200</td>
</tr>
<tr>
<td>Medion</td>
<td>8</td>
<td>1.9</td>
<td>5800</td>
</tr>
<tr>
<td>Modulion</td>
<td>39</td>
<td>9.4</td>
<td>7000</td>
</tr>
<tr>
<td>Ionotron a</td>
<td>11</td>
<td>2.6</td>
<td>6000</td>
</tr>
<tr>
<td>Ionotron b</td>
<td>82</td>
<td>19.7</td>
<td>6000</td>
</tr>
<tr>
<td>Ionotron c</td>
<td>11</td>
<td>2.6</td>
<td>9800</td>
</tr>
<tr>
<td>Ionotron d</td>
<td>83</td>
<td>19.9</td>
<td>9800</td>
</tr>
</tbody>
</table>

a - min. voltage, fan off, b - min. voltage, fan on, c - max. voltage, fan off, d - max. voltage, fan on.

The ambient conditions at the commencement of the test were: temperature 17.0°C, relative humidity 43%, negative ion concentration 800 ml$^{-1}$, positive ion concentration 960 ml$^{-1}$. Table 3-3 summarises the negative ion concentration measurements.

The ion concentration obtainable from an ion generator is seen to generally increase with increasing electrode potential, which is to be expected. One interesting feature of the Ionotron model is that when the fan is switched on, the ion concentration decreases.
This suggests that perhaps the motor driving the fan produces an excess number of positive ions.

Table 3-3: Negative Ion Concentrations Produced by Ion Generators

<table>
<thead>
<tr>
<th>Ion Generator</th>
<th>Distance from Electrode Points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0 m</td>
</tr>
<tr>
<td>Kit</td>
<td>3,000 ± 1,000</td>
</tr>
<tr>
<td>Medion</td>
<td>80,000 ± 10,000</td>
</tr>
<tr>
<td>Modulon</td>
<td>225,000 ± 5,000</td>
</tr>
<tr>
<td>Ionotron&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30,000 ± 8,000</td>
</tr>
<tr>
<td>Ionotron&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25,000 ± 5,000</td>
</tr>
<tr>
<td>Ionotron&lt;sup&gt;c&lt;/sup&gt;</td>
<td>&gt;250,000</td>
</tr>
<tr>
<td>Ionotron&lt;sup&gt;d&lt;/sup&gt;</td>
<td>&gt;250,000</td>
</tr>
</tbody>
</table>

<sup>a</sup> - min. voltage, fan off, <sup>b</sup> - min. voltage, fan on, <sup>c</sup> - max. voltage, fan off, <sup>d</sup> - max. voltage, fan on.

One criticism often made about negative ion generators is that the high voltages involved in their operation will produce ozone, possibly in harmful quantities. The United States Food and Drug Administration (FDA) sets an upper limit on the safe concentration of ozone at 0.05 parts per million (ppm).

The ozone concentration of the ion generators was measured with a Dasibi UV absorption ozone photo-
meter. This has an incremental sensitivity of 0.001 ppm and an accuracy of 3%. Ten measurements were made for each generator at 24 second intervals, at a distance of 10 cm from the electrode points. As a reference level, the ambient ozone concentration was measured, and all measurements were made in the room in which the ion concentration experiment was conducted.

The results are given in Table 3-4, and it was found that none of the negative ion generators tested produced an ozone concentration above the level set by FDA.

<table>
<thead>
<tr>
<th>Ion Generator</th>
<th>Ozone Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ambient</td>
<td>0.010</td>
</tr>
<tr>
<td>kit</td>
<td>0.010</td>
</tr>
<tr>
<td>Medion</td>
<td>0.012</td>
</tr>
<tr>
<td>Modulion</td>
<td>0.010</td>
</tr>
<tr>
<td>Ionotrona</td>
<td>0.010</td>
</tr>
<tr>
<td>Ionotrontb</td>
<td>0.008</td>
</tr>
<tr>
<td>Ionotrontc</td>
<td>0.011</td>
</tr>
<tr>
<td>Ionotrond</td>
<td>0.009</td>
</tr>
</tbody>
</table>

*a - min. voltage, fan off, b - min. voltage, fan on, c - max. voltage, fan off, d - max. voltage, fan on.
CHAPTER 4:

AIR ION MEASUREMENTS

Section 4-1: The "Blinker"

The simplest device for measuring the output of an ion generator is the "blinker", which is actually a crude relaxation oscillator. The circuit is shown in Figure 4-1 and a photograph of a blinker is shown in Figure 3-6.

As ions land on the antenna the capacitor will be charged. When the voltage across the capacitor is greater than the breakdown voltage of the neon (about 70 V) the neon conducts, emitting light. The capacitor continues to discharge in this way until the voltage reaches the extinguishing voltage of the neon, about 30 to 40 V. As the capacitor is discharged rapidly the light is emitted in a brief flash. When the neon stops conducting, charge builds up on the capacitor again and the process is repeated. The rate of flashing of the neon, then, is an indication of the rate of emission of ions. The diode is used so that only ions of one sign will operate the blinker. The blinker shown here is for use with negative ions; to measure positive ions the polarity of the diode would simply be reversed.
The "Blinker" circuit can be used to measure the current due to the ions being emitted. A probe developed by Beckart (1958) is illustrated in Figure 4-2. It consists of a circular ion collector-plate which is grounded via a d.c. amplifier and a sensitive ammeter, and a guard ring which surrounds the collector and is grounded directly. The current probes the ion collector plate, which is made of a thin sheet of metal coated with a highly conducting material. It also solves the problem that it cannot distinguish between ions of different mobilities.

**Figure 4-1:** "Blinker" circuit

**Figure 4-2:** Ion current probe
The blinker makes no distinction between ions of different mobilities, and only gives an approximate indication, in arbitrary units, of the rate of ionization. On the other hand, it can quickly show whether or not an ionizer is working, and it is extremely cheap and easy to construct.

Section 4-2: Ion Current Probe

An indication of the "ionizing power" of an artificial ionizer can be gained by measuring the current due to the ions being emitted. A probe developed by Beckett (1958) is illustrated in Figure 4-2. It consists of a circular ion collector-plate which is grounded via a d.c. amplifier and a sensitive ammeter, and a guard ring which surrounds the collector and is grounded directly.

The ion current probe does not measure the ion concentration but instead measures the number of ions passing through unit area per unit time. It is more quantitative than the "blinker" discussed above, but it also suffers from the problem that it cannot distinguish between ions of different mobilities.

Section 4-3: Ion Counters

Ion counters are devices which measure ion concentrat-
ion by sampling the air and forming an ion current in an applied electric field. The essential part of such a counter is the aspiration condenser, through which a stream of air to be analysed is maintained at constant speed. The most common type of condenser is based on the Zeleny method, shown in Figure 4-3. As shown it is set up to measure positive ion concentration; to measure negative ion concentration the polarity of $V$ is reversed.

The current, $I$, is measured directly and the ammeter can be calibrated in ions/ml according to the following relation:

$$n = \frac{I}{eQ}$$

$$= \frac{I}{evA}$$

$$= \frac{I}{(R^2 - r^2) \pi e v}$$

(4.1)

where $e$ is the electronic charge, $Q$ is the air flow, $A$ is the cross-sectional area of the collector, $v$ is the air velocity and $R$ and $r$ are the radii of the outer and inner cylinders respectively.

One advantage of the ion counter is that the geometry of the condenser determines a critical mobility such that ions of mobilities lower than this will not be collected. If $L$ is the length of the cylinders, $V$ is
Figure 4-3: Zeleny ion counter
the applied voltage and $x$ is the radial distance from the axis of the cylinders then the time for an ion to traverse the length of the collector will be given by

$$t_{\text{max}} = \frac{L}{V} \quad (4.2)$$

Now, the magnitude of the electric field between the cylinders is

$$E(x) = \frac{V}{x \ln \frac{R}{r}}$$

and

$$\frac{dx}{dt} = w E(x)$$

giving

$$\frac{dt}{t} = \frac{dx}{w E(x)}$$

$$\therefore \int_0^{t_{\text{max}}} dt = \int_0^R \frac{dx}{r w E(x)}$$

where the ion is considered to initially be near the outer electrode.

If the ion is to land on the collecting cylinder:

$$\int_0^{t_{\text{max}}} dt > \int_0^R \frac{dx}{r w E(x)}$$

$$\therefore t_{\text{max}} > \int_0^R \frac{x \ln \frac{R}{r}}{w V} dx \quad (4.3)$$
\[
\frac{L}{V} > \frac{R}{w} \left[ \frac{x^2}{2} \right] R \frac{1}{r} \\
\gg \frac{(R^2 - r^2)}{2 L w} \ln \frac{R}{r} \\
\therefore \quad w > \frac{V (R^2 - r^2)}{2 L V} \ln \frac{R}{r} \quad (4.3)
\]

or
\[
w > \frac{Q}{2 \pi L V} \ln \frac{R}{r} \quad (4.4)
\]

Equations (4.3) and (4.4) are equivalent ways of defining the critical mobility. However, some ions with mobilities less than this can be collected. Firstly, these ions may enter the condenser sufficiently close to the centre electrode to be deflected onto it, and secondly dust particles on the electrodes might cause whirls in the air flow to bring ion of all mobilities to the measuring electrode. The second effect is reduced if \( R \) is made large whilst \( r \) is kept as small as possible.

There is a minimum current which can be measured with the d.c. amplifier used, and for the minimum ion concentration that is to be analysed the minimum air flow is given by:

\[
Q_{\text{min}} = \frac{I_{\text{min}}}{e^{n_{\text{min}}}} \quad (4.5)
\]
Thus, to obtain a high ion current the air flow should be as high as possible. However, turbulence also increases with increasing air flow and this is calculated in terms of the Reynold's number, Re, which for a cylinder is given by:

\[ Re = \frac{v (R - r)}{2 \nu} \]  

(4.6)

where \( v \) is the mean velocity of air flow and \( \nu \) is the kinematic viscosity of air (\( \nu = 15.1 \times 10^{-6} \text{ m}^2/\text{s} \) at S.T.P.). In order for the air flow to be laminar, Re must be less than 580, and since Re is proportional to \((R-r)\), this implies that \((R-r)\) should be kept as small as possible to increase laminarity. This would, however, also reduce air flow and hence reduce the ion current, and is contrary to the condition discussed above that \( R \gg r \). The optimal design for an aspiration condenser, then, must involve compromises between the different conditions, which may vary for a portable or stationary ion counter.

Schmeer (1962) designed a condenser which could obtain a high ion current with a low Reynolds number by arranging seven cylindrical condensers, each with a small cross-section, in parallel (Figure 4-4). Another feature of this condenser is that the fringing effect of the electric field near the end of the cylinder is reduced by having the inner electrodes shorter than the outer ones.
A different way of reducing turbulence was used by Hoeg (1952), who used concentric cylindrical electrodes to laminarize the air flow.

Section 4-4: Median Mesospheric Ion Analyser

The most common part of this project was a median mesospheric ion analyser (Figure 4-4). The ion collector, which is shown on the diagram, consists of six parallel plates with a 3 mm thickness and an area of 10 cm².

The reason for this design of ion collector are

\[ \text{Figure 4-4: Multiple aspiration condenser of} \]
\[ \text{ion counter (see text)} \]
A different way of reducing turbulence was used by Hoegl (1962), who used concentric cylindrical electrodes to laminarize the air flow.

Section 4-4: Median Atmospheric Ion Analyser

The ion counter used in this project was a Median Atmospheric Ion Analyser Type 134A (Figure 4-5). The collector design of this model differs from the types discussed above in that it employs parallel plates instead of cylindrical ones, and is shown schematically in Figure 4-6.

The reasons for this design of ion collector are found in the equations for ion concentration and limiting ion mobility (4.1):

\[ n = \frac{I}{dV A} = \frac{I}{2e v h d} \]  \hspace{1cm} (4.7)

where \( A \) is the cross-sectional area of the ion collector.

The limiting ion mobility for a parallel plate collector is calculated in a similar fashion to the cylindrical collector case. If \( u \) is the velocity of an ion of mobility \( w \) then

\[ u = w E = \frac{w V}{d} \]  \hspace{1cm} (4.8)

If the ion enters the collector just near the polarizing plate then the time to move to the collecting plate
FIGURE 4-5: Medion Atmospheric Ion Analyser Type 134A
Figure 4-6: Schematic of Medion Ion Analyzer
will be given by

\[ t = \frac{d}{u} = \frac{d^2}{wV} \]

Since the maximum time an ion can spend in the collector is \( t_{\text{max}} = L/v \), an ion can only be collected if

\[ t > \frac{d^2}{wV} \]

\[ \frac{L}{v} > \frac{d^2}{wV} \]

\[ w > \frac{d^2v}{LV} \] \hspace{1cm} (4.9)

c.f. (4.3)

As with the cylindrical collector the velocity of the air must be kept low to reduce turbulence, so in order to keep the ion current at a reasonable level the area of the collector plates must be relatively large. In a parallel plate collector the cross-sectional area can be increased by increasing the height of the plates while keeping \( d \) constant. Thus, the limiting mobility given by (4.9) is also constant.

Stray electric fields can cause an ion counter to give spurious values for ion concentration. To protect the Medion Analyser from such effects its collector plates are positioned 2 cm in front of the polarizing plates in order to reduce the fringing of the electric field near the inlet of the collector. Fringing effects
are further reduced by the grounded duct around the inlet.

The air speed at the inlet is set at 2.0 m/s at the factory. The accuracy of this is critical since it affects both the calibration of ion concentration and the limiting mobility, and has a probable error of ± 2% (Beckett, 1961). The following physical parameters were measured in order to calculate the ion current per unit ion concentration and the limiting mobility. The main source of error in linear measurements is that due to the collector's delicate nature the measurements had to be made with it intact and in situ in the analyser.

\[
\begin{align*}
{d} & = 10 \text{ mm} \pm 0.1 \text{ mm} \\
{h} & = 77 \text{ mm} \pm 1 \text{ mm} \\
{L} & = 210 \text{ mm} \pm 1 \text{ mm} \\
|V| & = 192 \text{ V} \pm 1 \text{ V}
\end{align*}
\]

The limiting mobility is

\[
\begin{align*}
{W_{\text{lim}}} & = \frac{{d^2v}}{{LV}} \\
& = \frac{{(1.0 \text{ cm} \pm 1\%)^2 \times (200 \text{ cm/s} \pm 2\%)}}{{(21.0 \text{ cm} \pm 0.5\%) \times (192\text{V} \pm 0.5\%)}} \\
& = 0.050 \text{ cm}^2/\text{V.s} \pm 5\%
\end{align*}
\]

This means that only small and intermediate ions are collected.
From (4.7) the ion current per unit ion concentration is given by

\[ \frac{I}{n} = 2e \nu h d \]

\[ = 2 \times 1.6 \times 10^{-19} \text{C} \times (200 \text{cm/s} \pm 2\%) \times (7.7 \text{cm} \pm 1.3\%) \times (1.0 \text{cm} \pm 1\%) \]

\[ = 4.9 \times 10^{-16} \text{A/ion/ml} \pm 4.3\% \]

The ion current passes through a d.c. amplifier with a current gain of \(4 \times 10^{8}\), giving an overall sensitivity of about \(2 \times 10^{-7} \text{A/ion/ml}\). This current is measured by a milliammeter with a full scale deflection of 1 mA, corresponding to an ion concentration of 5000 ions/ml full scale. However, the Medion Analyser can measure ion concentrations in other ranges by changing the resistor \(R\) (Figure 4-6). Four concentration ranges are available, with full scale values of 1,000, 5,000, 50,000 and 250,000 ions/ml.
CHAPTER 5:

SMALL AIR ION CONCENTRATION

Section 5-1: Outdoor Ion Concentration

The diurnal and seasonal variations in small ion concentrations in open air, and the effect of various meteorological elements on ion concentration, have been investigated by Davis (1961), Holzer (1955), Israel (1957), Robinson and Dirnfeld (1963), Ruhnke (1961), Schmeer and Hock (1962) and Siksna (1953). The most important points are summarized here.

Schmeer and Hock measured the ion concentration in Upper Bavaria during the months August to October, and the mean diurnal variation for this period is shown in Figure 5-1. The concentration of ions of both polarities is very approximately sinusoidal, with a maximum at 6 a.m. and minimum at 5 p.m.

As part of their comprehensive research on ion concentration a similar survey was conducted by Robinson and Dirnfeld in Israel during the period 7-10 August, 1960 (Figure 5-2). The curves exhibit the same profile as those in Figure 5-1 but the concentration maxima and minima occur at 9 a.m. and 3 p.m. respectively. This is not surprising, as the differences in local geology and climate are considerable. They further found that the ionization maximum coincides with the maximum of airborne radioactivity.
Of particular interest are the concentration measurements made by Robinson and Birnbaum during the "chasmal" period of 30 August to 5 September, 1964. This weather condition is characterized by a rapid rise in temperature and a sudden increase in wind that brings about by dry weather conditions. Dry weather conditions are known as the "hurricane" in the Maritime Provinces (Canada), the "Sante Ana" in Southern California, and the "Foehn" and the Pooh in Switzerland.

The unique feature of the "chasmal" is that the concentration of positive ions increases considerably.

Figure 5-1: Diurnal variation of small ion concentration

Concentration occurred five hours later than in "normal" weather, but this is not a necessary feature of chasmal conditions.

Figure 5-2: Ion concentration in "normal" weather

The effect of humidity on ion concentration is shown in Figure 5-1. The two days had similar weather conditions.
Of particular interest are the concentration measurements made by Robinson and Dirnfeld during the "chamsin" period of 30 August to 5 September, 1960. This weather condition is characterised by a rapid rise in temperature and decrease in humidity brought about by the arrival of hot dry winds. These winds are known as the Sharaf in Israel, but are known as the Santa Ana in Southern California, the Chinook in Canada, and the Foehn in Switzerland and Central Europe.

The unique feature of the "chamsin" is that the concentration of positive ions increases considerably, as does the ratio $n^+ / n^-$ (Figure 5-3). The maximum concentration occurred five hours later than in "normal" weather, but this is not a necessary feature of chamsin conditions.

Preceding the arrival of the Sharaf and for the duration of the chamsin, people sensitive to the conditions suffer from depression, migraine, nausea, insomnia and respiratory difficulties (Krueger, 1973). It seems that temperature and humidity alone cannot be responsible for this, as Robinson and Dirnfeld note that such people are not adversely affected by the hot dry weather of other regions. They also found that when the Sharaf was approaching, positive ionization increased ten to twelve hours before any measurable change in other meteorological parameters.

The effect of humidity on ion concentration is shown in Figure 5-4. The two days had similar weather,
except that on 6 March the relative humidity was 82% and 38% on 13 April, which would correspond with an increase in rainfall concentration. The measurements were also made on a day when rain fell for 12 hours, as is shown in Figure 5-3.

During the course of the experiment, the ion concentration in both polarities of ions doubled, and the ratio $N^+ / N^-$ changed from 1.3 to 4.4. The general increase in ion concentrations from the atmosphere while the excess negative ions are produced by the Lenz effect.

Figure 5-3: Ion concentration in chamsin conditions

Figure 5-4: Ion concentration in (a) humid and (b) dry weather
except that on 8 March the relative humidity was 82% and 38% on 10 March. An increase in humidity corresponds with an increase in ions of both signs.

Rainfall has a dramatic effect on ion concentration. The measurements taken by Robinson and Dirnfeld on a day when rain fell between 1 p.m. and 3 p.m. are shown in Figure 5-5.

During the rainfall the concentration of both polarities of ions doubled, and the ratio $n^+ / n^-$ changed from 1.2 to 0.9. The general increase in ionization is due to the rain washing out condensation nuclei from the atmosphere while the excess negative ions are produced by the Lenard effect.

Section 5-2: Indoor Ion Concentration

The indoor small ion concentration has generally been found to be higher than that outdoors (Dessauer, Fraffunder and Lamb (1955/56), and Schilling and Carson (1953)). This additional ionization is caused by the emission of radiation by radioactive material within the walls and by secondary radiation being released after the wall is struck by cosmic rays. Also, the condensation nuclei concentration tends to be lower in closed rooms. The diurnal variation of indoor ion concentration has been found to be very close to that in open air, but Dessauer et al. also
noticed concentration fluctuations with periods of between a half a second to one minute.

Belon and Holzer (1955) sealed a room with plastic sheets and shielded it with a bronze screen. They found that ion concentration increased steadily to a maximum after sixty hours and that diurnal variations disappeared. Jones, Maddever and Sanders (1959) performed a similar experiment and showed that the increase in ions is accompanied by a decrease in the concentration of nuclei.

The effect of nuclei on small ion concentration was further demonstrated by Hoegl (1962). The ion concentration in a sealed room was at a maximum outside of working hours when nuclei were not being stirred up by vibrations from adjacent rooms. Results of a similar experiment by Schmeer are shown in Figure 5-6.

Section 5-3: Air Ion Concentrations in Canberra

The concentration of negative and positive small air ions in several suburbs of Canberra, A.C.T., was measured with the Medion Atmospheric Ion Analyser described in Section 4-4. The measurements were taken as close as possible to noon on two fine, calm days, and the temperature and relative humidity at each site was measured with a wet and dry bulb thermometer. The results are given in Table 5-1.
Figure 5-5: Effect of rainfall on ion concentration

Figure 5-6: Variation of small ion concentration in a sealed room
Table 5-1: Air Ion Concentrations in Canberra

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Temp (°C)</th>
<th>Relative Humidity (%)</th>
<th>n⁻ (ml⁻¹)</th>
<th>n⁺ (ml⁻¹)</th>
<th>n⁺/n⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/9/81</td>
<td>11:20</td>
<td>Black Mtnᵃ</td>
<td>16.5</td>
<td>70</td>
<td>600</td>
<td>900</td>
<td>1.5</td>
</tr>
<tr>
<td>13/9/81</td>
<td>11:50</td>
<td>Civic</td>
<td>19.5</td>
<td>39</td>
<td>900</td>
<td>1200</td>
<td>1.3</td>
</tr>
<tr>
<td>13/9/81</td>
<td>12:15</td>
<td>Lake Burley Griffin</td>
<td>18.0</td>
<td>40</td>
<td>900</td>
<td>900</td>
<td>1.0</td>
</tr>
<tr>
<td>13/9/81</td>
<td>12:40</td>
<td>Griffith</td>
<td>16.5</td>
<td>45</td>
<td>1300</td>
<td>1200</td>
<td>0.9</td>
</tr>
<tr>
<td>15/9/81</td>
<td>11:41</td>
<td>Mt Ainslieᵇ</td>
<td>17.0</td>
<td>47</td>
<td>600</td>
<td>1300</td>
<td>2.2</td>
</tr>
<tr>
<td>15/9/81</td>
<td>12:18</td>
<td>Red Hillᶜ</td>
<td>20.0</td>
<td>48</td>
<td>900</td>
<td>900</td>
<td>1.0</td>
</tr>
<tr>
<td>15/9/81</td>
<td>12:47</td>
<td>Civic</td>
<td>20.0</td>
<td>40</td>
<td>1000</td>
<td>800</td>
<td>0.8</td>
</tr>
</tbody>
</table>

ᵃ - 812 m    ᵇ - 842 m    ᶜ - 722 m

Figure 5-7 is a plot of positive ion concentration versus negative ion concentration and this shows the wide spread in natural outdoor ion concentration.

Section 5-4: Indoor Ion Concentration Measurements

A series of measurements of the indoor air ion concentration was conducted in the room described in Section 3-5. Each of the measurements was taken within half an hour of noon in order to avoid the effect of diurnal variations. Temperature and relative humidity were also measured and their influence on ion concentration investigated.
Table 5-2: Indoor Ion Concentration Measurements

<table>
<thead>
<tr>
<th>Date</th>
<th>Temp (°C)</th>
<th>Relative Humidity (%)</th>
<th>n⁻ (ml⁻¹)</th>
<th>n⁺ (ml⁻¹)</th>
<th>n⁺/n⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>29/4/81</td>
<td>14.5</td>
<td>48</td>
<td>800</td>
<td>1050</td>
<td>1.31</td>
</tr>
<tr>
<td>30/4/81</td>
<td>13.0</td>
<td>55</td>
<td>640</td>
<td>740</td>
<td>1.16</td>
</tr>
<tr>
<td>5/5/81</td>
<td>15.5</td>
<td>54</td>
<td>760</td>
<td>840</td>
<td>1.11</td>
</tr>
<tr>
<td>8/5/81</td>
<td>14.0</td>
<td>57</td>
<td>900</td>
<td>1020</td>
<td>1.13</td>
</tr>
<tr>
<td>11/5/81</td>
<td>11.5</td>
<td>64</td>
<td>960</td>
<td>1050</td>
<td>1.09</td>
</tr>
<tr>
<td>13/5/81</td>
<td>12.5</td>
<td>60</td>
<td>620</td>
<td>760</td>
<td>1.23</td>
</tr>
<tr>
<td>14/5/81</td>
<td>12.5</td>
<td>60</td>
<td>500</td>
<td>540</td>
<td>1.00</td>
</tr>
<tr>
<td>19/5/81</td>
<td>10.0</td>
<td>62</td>
<td>700</td>
<td>800</td>
<td>1.14</td>
</tr>
<tr>
<td>22/5/81</td>
<td>13.0</td>
<td>77</td>
<td>820</td>
<td>920</td>
<td>1.12</td>
</tr>
<tr>
<td>23/5/81</td>
<td>16.5</td>
<td>75</td>
<td>1000</td>
<td>1050</td>
<td>1.05</td>
</tr>
<tr>
<td>24/5/81</td>
<td>17.0</td>
<td>65</td>
<td>1000</td>
<td>1100</td>
<td>1.10</td>
</tr>
<tr>
<td>25/5/81</td>
<td>17.5</td>
<td>57</td>
<td>720</td>
<td>820</td>
<td>1.14</td>
</tr>
<tr>
<td>26/5/81</td>
<td>18.5</td>
<td>64</td>
<td>680</td>
<td>1000</td>
<td>1.47</td>
</tr>
<tr>
<td>28/5/81</td>
<td>18.5</td>
<td>61</td>
<td>800</td>
<td>1100</td>
<td>1.38</td>
</tr>
<tr>
<td>2/6/81</td>
<td>17.0</td>
<td>61</td>
<td>800</td>
<td>840</td>
<td>1.05</td>
</tr>
<tr>
<td>3/6/81</td>
<td>16.5</td>
<td>60</td>
<td>900</td>
<td>840</td>
<td>0.93</td>
</tr>
<tr>
<td>5/6/81</td>
<td>16.0</td>
<td>43</td>
<td>440</td>
<td>520</td>
<td>1.18</td>
</tr>
<tr>
<td>6/6/81</td>
<td>15.0</td>
<td>48</td>
<td>500</td>
<td>600</td>
<td>1.20</td>
</tr>
<tr>
<td>7/6/81</td>
<td>13.5</td>
<td>51</td>
<td>880</td>
<td>1000</td>
<td>1.14</td>
</tr>
<tr>
<td>8/6/81</td>
<td>12.5</td>
<td>55</td>
<td>640</td>
<td>700</td>
<td>1.09</td>
</tr>
<tr>
<td>9/6/81</td>
<td>12.5</td>
<td>60</td>
<td>680</td>
<td>880</td>
<td>1.29</td>
</tr>
<tr>
<td>11/6/81</td>
<td>15.0</td>
<td>58</td>
<td>660</td>
<td>520</td>
<td>0.79</td>
</tr>
<tr>
<td>12/6/81</td>
<td>14.5</td>
<td>53</td>
<td>640</td>
<td>920</td>
<td>1.44</td>
</tr>
<tr>
<td>15/6/81</td>
<td>13.5</td>
<td>61</td>
<td>500</td>
<td>500</td>
<td>1.00</td>
</tr>
<tr>
<td>19/6/81</td>
<td>13.5</td>
<td>51</td>
<td>440</td>
<td>240</td>
<td>0.55</td>
</tr>
<tr>
<td>22/6/81</td>
<td>16.5</td>
<td>60</td>
<td>660</td>
<td>560</td>
<td>0.85</td>
</tr>
<tr>
<td>23/6/81</td>
<td>16.0</td>
<td>50</td>
<td>680</td>
<td>760</td>
<td>1.12</td>
</tr>
<tr>
<td>24/6/81</td>
<td>14.5</td>
<td>58</td>
<td>540</td>
<td>640</td>
<td>1.19</td>
</tr>
</tbody>
</table>

In Figure 5-8 positive ion concentration is plotted against negative ion concentration. In general n⁺
is greater than \( n^2 \) and the relationship between these appears to be approximately linear. When a least squares linear regression is performed on these data, the resultant line has the equation \( n^2 = 0.341 n + 0.31 \) with a correlation coefficient of 0.93.

The course of \( n \) and \( n^2 \) over the period 1/2/80 to 23/6/81 is graphed in Figure 5-8. Figure 5-9 shows the temperature and relative humidity for the same period. The profiles of the ion concentration curves are similar to each other and to the humidity curve. There appears to be no correlation with temperature, however.

When the ion concentration is plotted against relative humidity (Figures 3-10 and 3-11) it is seen that concentration tends to increase with humidity. This is in agreement with the work of Amihen and Blinfield. The lines of best fit through these points have the following equations and correlation coefficients:

\[ n^2 = 11.1 \times \text{relative humidity} + 6.5 \quad r = 0.81 \]
\[ n = 11.2 \times \text{relative humidity} + 14.4 \quad r = 0.82 \]

It is interesting to note that the ratio \( n^2/n \) is independent of humidity. Figure 3-12 shows \( n^2/n \) plotted against relative humidity, but there does not appear to be any correlation between them. This would suggest that an increase in relative humidity aids the formation...
is greater than $n^-$ and the relationship between them appears to be approximately linear. When a least-squares linear regression is performed on these data the resultant line has the equation $n^+ = 1.15n^- - 17$, with a correlation coefficient of 0.85.

The course of $n^-$ and $n^+$ over the period 29/4/81 to 23/6/81 is graphed in Figure 5-9. Figure 5-10 shows the temperature and relative humidity for the same period. The profiles of the ion concentration curves are similar to each other and to the humidity curve. There appears to be no correlation with temperature, however.

When ion concentration is plotted against relative humidity (Figures 5-10 and 5-11) it is seen that concentration tends to increase with humidity. This is in agreement with the work of Robinson and Dirnfeld. The lines of best fit through these points have the following equations and correlation coefficients:

$$n^- = 11.1 \times\text{relative humidity (}) + 65 \quad r = 0.51$$
$$n^+ = 11.2 \times\text{relative humidity (}) + 144 \quad r = 0.38$$

It is interesting to note that the ratio $n^+/n^-$ is independent of humidity. Figure 5-12 shows $n^+/n^-$ plotted against relative humidity, but there does not appear to be any correlation between them. This would suggest that an increase in relative humidity aids the formation of small air ions, but that the proportional increase is
independent of the sign of ion. More research is necessary to establish this, but it does appear feasible in the light of the reaction schemes discussed in Section 2-9.
FIGURE 5-9: Course of ion concentration in Canberra
FIGURE 5-10: Course of Temperature and relative humidity in Canberra
FIGURE 5-11a: $n^+$ versus relative humidity
FIGURE 5-11b: $n^-$ versus relative humidity
FIGURE 5-12: \( n^+ / n^- \) versus relative humidity
Chapter 6:

Review of Previous Work on the Influence of Air Ions on Human Reaction Time

Section 6-1: Knoll, Leonard and Hightberg

The possible effect of air ions on reaction time has been mooted since their discovery, but until recently reports of such effects have tended to deal with single cases. The first statistically valid work was conducted by Knoll, Leonard and Hightberg (1956).

The experimental setup is shown schematically in Figure 6-1. A Geiger-Muller tube in the presence of a radioactive source was used as a random pulse generator. The rate of pulses from this was limited by a pulse repetition filter and the output of the filter used to initiate the stimulus, which was a light spot appearing momentarily on a cathode ray oscilloscope. The subject was to respond to this by depressing a switch held in a comfortable position, and the time between the appearance of the light spot and the closing of the switch known as the "reaction time". This was measured by an electronic counter in units of milliseconds. The ionizer used was a Polonium-foil-type, described in Section 3-1. The ion polarity was changed by changing the bias voltage polarity, and the ionized air blown towards the subject at a rate of about \(3.8 \times 10^4\) ml/s. Ion density
was measured with plate condenser-type ion analysers. Unfortunately the limiting ion mobility of the analysers was not given.

Each subject participated in a three and a half hour session of reaction time tests. During these sessions there were half-hour periods of air ionization in the following sequence: ambient, positive, ambient, negative, ambient, positive, and ambient. Ten reaction time measurements were taken every five minutes, and these values averaged to give the data points.

The data were analysed by phase shift integration. The raw data points were assigned to groups of three and averaged. For phase I every third data point starting at the first point were used, for phase II data points starting at the second point were used, and similarly for phase III. The three phases were then plotted as functions of time to see if they exhibited any correlation with the ionization state of the atmosphere.

It was found that:

1) An atmosphere of either polarity may increase one individual's reaction but decrease another's.

2) Ions of the same polarity may decrease an individual's reaction time and then increase it a few hours later.

3) The changes in reaction time are small, with a maximum change of 10 per cent.
FIGURE 6-1: Experimental set-up
Section 6-2: Rheinstein

The first experiment in this field to produce statistically significant results was that of Rheinstein (1959). Several hundred subjects participated in this study which involved over twelve thousand tests.

Rheinstein used an experimental setup similar to that of Figure 6-1, except that the stimulus used was the flashing of a gas discharge lamp. A tritium-type ion generator, as described in Section 3-1, was used, and the ions moved electrostatically. An automatic switching unit was developed which changed the polarity of the bias electrode to a positive, negative, or ground potential. Thus, neither the subject nor the experimenter knew whether the air had positive, negative or ambient ionization.

Rheinstein chose to measure the ion current incident on the subject, as opposed to the ion concentration, claiming that the latter was "not applicable". He gives no reason for this, and it should be noted that this was an inappropriate choice as it is now believed that only small air ions are biologically active, and the readings for ion current would include a contribution from large ions.

When the subject was ready to commence he would depress a morse key. After a period of one to ten seconds the lamp would flash and the subject would release the key as quickly as possible. This was repeated about
five times per minute, and the air ionization changed at three minute intervals as described above. Each experiment involved one period each of positive and negative ionization, and two periods of ambient conditions, totalling twelve minutes per experiment.

As there can be a wide variation in reaction times for a given subject at different times, the individual experiments were not analysed. Instead, the results of each series of experiments were statistically analysed in the following manner:

The average reaction time in each experiment was used as an arbitrary reference point, and individual reaction times expressed as a percentage deviation from this. The results for the series were then combined to form three statistical distributions. One distribution consisted of all data obtained when no ions were being produced, one consisted of data obtained when positive ions were generated and the third consisted of data obtained when negative ions were generated. The distributions that resulted when ion currents of $2 \times 10^9$ ions/second were used are shown in Figure 6-2. A modified form of Student's t-test (see Hald, 1952) showed that the distributions of reaction times were different at a significance level of 0.05%.

From Figure 6-2 it can be seen that when artificial ions of either polarity were produced there was usually a change in reaction time. However, an increase in
FIGURE 6-2: Reaction time distributions - negative and positive ions
FIGURE 6-3: Reaction time distributions - negative ions

FIGURE 6-4: Reaction time distributions - positive ions
reaction time occurred about as often as a decrease. In another series of experiments only negative ions were produced, but with two different ion currents, viz. $2 \times 10^9$ ions/second and $6 \times 10^8$ ions/second. These correspond to approximate ion concentrations of $10^6$ ions/cm$^3$ and $3 \times 10^5$ ions/cm$^3$ respectively. The results are shown in Figure 6-3. It can be seen that in the lower ion concentration the reaction time decreased in a larger percentage of cases. This was found to be true for other ion currents, and was also the case when positive ions were generated.

When ion concentrations of 2000 ions/ml were produced, the influence on reaction time was more pronounced. For both signs of ions reaction times were decreased in nearly 90% of cases. Figure 6-4 shows the effect of positive ions of this concentration on reaction time; negative ions had a similar effect.

In general, it would appear from this series of experiments that at very high concentrations, positive and negative ions sometimes increase and sometimes decrease reaction times, but at more moderate concentrations reaction times usually are decreased.

Section 6-3: Halcomb and Kirk

Halcomb and Kirk (1965) studied the influence of air ionization on the performance of a vigilance task.
A vigilance task is defined as a task which "requires the detection of serially presented stimuli during long work periods when the individual has little or no prior knowledge of the spatial pattern or temporal sequence of the stimuli" (Kirk and Hecht, 1963).

The task in this experiment was a four hour series of reaction time tests. The stimulus was a quarter-second deflection of a horizontal beam on a cathode ray tube, and the periods between stimuli ranged from a half to three and a half minutes. Twenty subjects performed this task in an atmosphere that was positively ionized, and twenty in an atmosphere that was negatively ionized. The ion concentrations were about 10,000 ions/ml in both cases, and the subjects were not aware of the ionization conditions.

Figure 6-5 compares the mean log reaction time of subjects performing in positive and negative ionization of the air. Subjects in the negatively ionized air had a slower decrement in performance than those subjects which were in the positively ionized atmosphere. Analysis of variance shows that this difference is statistically significant in the third eighty-minute period. This is summarized in Table 6-1.

Table 6-1: Analysis of Effects of Ionization During the Three Eighty-Minute Periods

<table>
<thead>
<tr>
<th>Source of Variance</th>
<th>df</th>
<th>mean square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between ionization</td>
<td>3</td>
<td>0.01865</td>
<td>0.39</td>
<td>ns</td>
</tr>
<tr>
<td>during 1st time period</td>
<td>1</td>
<td>0.02859</td>
<td>0.60</td>
<td>ns</td>
</tr>
<tr>
<td>during 2nd time period</td>
<td>1</td>
<td>0.30730</td>
<td>6.43</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>during 3rd time period</td>
<td>1</td>
<td>0.04781</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>114</td>
<td>0.04781</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6-5: Course of reaction time over four hours
Section 6-4: Hawkins and Barker

Hawkins and Barker (1978) tested the effect of air ionization on psychomotor tasks, including visual and auditory reaction time tests. Forty-five male subjects were randomly divided into three groups, with each group performing the tasks in an atmosphere of either positive, negative or natural ionization. A corona-discharge-type ionizer was used, and the subjects were ignorant of the ionization conditions.

In order to minimise the effects of other parameters on performance the tests were carried out in a controlled environment. Temperature and humidity were held constant and subjects wore only a light cotton overall. To prevent a build-up of static charge, which might influence the ion concentration near the subjects, they had an earthing strap placed on their ankles. One hour was allowed for acclimatization in the chamber, and the tasks performed in the following hour. The average ion concentrations for each of the three groups are given in Table 6-2.

Table 6-2: Average Ion Concentrations

<table>
<thead>
<tr>
<th>Group</th>
<th>$n^+$ (ml$^{-1}$)</th>
<th>$n^-$ (ml$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>natural</td>
<td>223</td>
<td>146</td>
</tr>
<tr>
<td>negative</td>
<td>252</td>
<td>4197</td>
</tr>
<tr>
<td>positive</td>
<td>4576</td>
<td>252</td>
</tr>
</tbody>
</table>
Each subject repeated the reaction time tests sequentially fifty times at various times of the day, ranging from 9.00 a.m. to 9 p.m. Table 6-3 summarizes the overall means and standard deviations for the reaction times of the three groups.

### Table 6-3: Mean Reaction Time ± Standard Deviation (ms)

<table>
<thead>
<tr>
<th>Task</th>
<th>Negative ionization</th>
<th>Positive ionization</th>
<th>Natural ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual reaction time</td>
<td>197.00±24.90</td>
<td>209.60±17.81</td>
<td>209.87±17.50</td>
</tr>
<tr>
<td>Auditory reaction time</td>
<td>158.13±14.29</td>
<td>164.47±14.73</td>
<td>167.93±23.36</td>
</tr>
</tbody>
</table>

The circadian rhythm causes reaction time to vary throughout the day, so to account for this the data were analysed with a two-way analysis of variance. This showed that reaction times changed significantly when performed in a negatively ionized atmosphere (Table 6-4). There was no significant difference between the results for the positive and natural ionization groups.

### Table 6-4: Between-Group Variation

<table>
<thead>
<tr>
<th>Task</th>
<th>Negative vs. natural</th>
<th>Positive vs. natural</th>
<th>Negative vs. positive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>p</td>
<td>F</td>
</tr>
<tr>
<td>Visual reaction time</td>
<td>25.60 &lt;0.001</td>
<td>0.014 &gt;0.1</td>
<td>18.77 &lt;0.001</td>
</tr>
<tr>
<td>Auditory reaction time</td>
<td>23.98 &lt;0.001</td>
<td>1.76 &gt;0.1</td>
<td>9.65 ≠0.005</td>
</tr>
</tbody>
</table>
An interesting finding of this research was that the circadian rhythm is influenced by air ionization. Subjects in controlled conditions had an increasing level of performance between 9.00 a.m. and 4.00 p.m. but thereafter their performance steadily declined. The group in negative ionization maintained performance throughout the evening period, while that of the group in a positively ionized atmosphere declined at a faster rate than that of the control group. These changes are statistically significant (Table 6-5).

<table>
<thead>
<tr>
<th>Task</th>
<th>Negative vs. control</th>
<th>Positive vs. control</th>
<th>Negative vs. positive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>p</td>
<td>F</td>
</tr>
<tr>
<td>Visual reaction time</td>
<td>6.80 &lt;0.001</td>
<td>3.78 &lt;0.001</td>
<td>7.63 &lt;0.001</td>
</tr>
<tr>
<td>Auditory reaction time</td>
<td>7.85 &lt;0.001</td>
<td>6.53 &lt;0.001</td>
<td>3.38 &lt;0.001</td>
</tr>
</tbody>
</table>

The work of Hawkins and Barker has shown that under carefully controlled conditions air ion levels affect the performance of certain psychomotor tasks. In particular, both visual and auditory reaction time were influenced by air ionization. Firstly, negative ions decreased reaction times but positive ions had no overall effect. Secondly, breathing ions of either polarity gave rise to a change in circadian rhythm.
CHAPTER 7:

PRELIMINARY EXPERIMENT

Section 7-1: Aim

Research by other workers, outlined in Chapter 6, indicates that air ionization effects psychomotor performance. In the most carefully controlled experiment, that of Hawkins and Barker, human reaction time was shown unambiguously to be decreased by an average of 6.1% by the breathing of negative air ions. However, these results were derived under somewhat artificial conditions. In a "normal" work situation people are not earthed and do not wear standardized clothing. They conclude their paper by saying that "much work needs to be done on the industrial application of these findings".

The purpose of the present research is to investigate the influence of negative air ions on reaction time in a common work environment. Apart from the installation of negative ion generators the environment is to remain in its usual state. Although the ambient temperature and relative humidity were measured, no attempt was made to control these factors. Another major difference between this research and that of Hawkins and Barker is that the subjects are not to be earthed as this would restrict the subjects in the performance of their work.

A common deficiency in research on air ions is that the ion concentration used is not always measured,
or at least it is not reported. Further, when ion concentration is given it usually includes a component due to large air ions which are not believed to be biologically active. This is possibly due to the large ions, with diameters of around $10^{-7}$ m, being filtered from the air in the upper respiratory passages.

A preliminary trial was conducted, before commencing a more extensive series of experiments, in order to develop the most efficient experimental design and to check the performance of the equipment.

Section 7-2: Experimental Design Considerations

The crux of experimentation of this nature is to manipulate independent variables and determine whether this effects one or more dependent variables. In this case the independent variables are air ionization and time of day, and the dependent variable is reaction time. Experimental designs appropriate for this experiment are the between-subject and within-subject designs.

In a between-subjects design each subject receives only one level of each independent variable. Subjects can be randomly assigned to groups to ensure that the groups are equivalent prior to the introduction of the independent variable. Differences in performance can then be attributed to the independent variable. If the dependent variable is believed to be related to a
subject variable, for example age or I.Q., then a matched-groups design may be preferable. This is a between-subjects design in which subjects are assigned to groups according to subject variable, giving greater assurance of group equivalence and reducing within-group variance. In a within-subject design each subject is tested at every level of other independent variables. As more information is obtained from each subject than in a between-subject design fewer subjects are needed. The effect of the independent variable is assessed by the change in performance of individuals rather than groups. Since chance fluctuations in performance of one person at two times tend to be less than those between two people at the same time, a within-subject design can sometimes detect effects which cannot be detected with a between-subjects design. The major problem with within-subjects designs is the control of non-manipulated variables, especially time-related variables such as fatigue or learning. The effects of non-manipulated variables can be distributed over the treatment variables by the technique of counterbalancing, which involves varying the order of treatments that each subject experiences.

Section 7-3: Method

The subjects for this experiment were volunteer
female secretaries of the Faculty of Science at the Australian National University. The reasons for this choice were that they represented a population with similar work responsibilities and environments, and that their location on campus was very convenient.

Four subjects were involved in the preliminary experiments. All were told that the experiment concerned negative air ionization and its effect on reaction time. It would have been preferable to have them ignorant of this but this was not possible for two reasons. Firstly, the prospective subjects and their Heads of Departments required to know the nature of the project before agreeing to participate. Secondly, the tests were to be conducted in the subjects' offices and there was no practical way of installing ionizers without their knowledge.

Before the experiment began all subjects were shown the reaction timer. Its operation was explained to them (see Section 7-4) and a set of reaction time measurements conducted so that they could familiarize themselves with its use.

Each subject then participated in a series of tests on four consecutive working days. Their reaction time was measured ten times in succession at six times of the day viz. 10 a.m., 11 a.m., 12 noon, 2 p.m., 3 p.m. and 4 p.m. Ionizers were installed in the offices at 9 a.m. on all four days. On two of the days the ionizer was working normally, and was placed about one metre
from the subject's usual seating position to make an ion concentration of at least 100,000 ml\(^{-1}\) available to her. However, on the other two days the ionizer was adjusted, as described in Section 7-4, so that it appeared to be working but did not actually emit ions. The order in which a subject had the ionizers had the pattern A-B-B-A, and because of the double-blind nature of the experiment an assistant determined whether a subject received an active or inactive generator first. This was revealed to the experimenter at the conclusion of the experiment.

At the end of each day the following questions were asked:

i) Are you currently taking any medication or drugs?

ii) Did you think that the ion generator was working today?

iii) If so, do you think that it had a detrimental effect/a beneficial effect/no effect?

The first question was necessary to check that their reactions were not being influenced by drugs. The second was to evaluate the disguising of the ionizers and the third was to gain an idea of what effect the subjects thought that negative ions had on them.

As it was not practicable to measure the ion concentration at each test this was done only once per day after the noon test. Poulton (1970) warns that "measurements of ion concentration and psychological
testing should not be performed simultaneously" because the act of measuring the concentration may draw ions away from the subject. The ion concentration would indicate which ionizers was in use so this measurement was done by an assistant. Temperature and relative humidity were also measured.

In order to complete the experiment in as short a time as possible, on a given day two subjects were being tested. One would have an active ionizer and the other an inactive ionizer. In each of the six time periods the two subjects had their reaction time tests in succession, so that there was only a time difference between the tests of around five or six minutes.

Section 7-4: Apparatus

This experiment required negative ion generators which are either in an operative or non-operative state. Generators that were operative produced negative ions in the usual manner, while non-operative generators must have the appearance of working normally but emit no ions. As the experiment is double-blind it is important that the generators be indistinguishable from each other, to both the subjects and the experimenter.

Modulion negative ion generators were modified by the method of Stevens (1982) to disguise their operative state. Each generator was placed in a wooden box
of dimensions 22.5 cm x 15.4 cm x 14.5 cm, the front panel of which was removed and replaced with wire mesh. This mesh was connected to the high voltage discharge-point supply via a double-pole single-throw switch (switch S1 in Figure 7-2). Also, a wire positioned between the generator and mesh was grounded via S1.

When the generators are required to emit ions S1 is open. Then the potentials of the "earth wire" and mesh are floating, but in practice they quickly reach equilibrium at -3.8 kV. The effect of this on ion concentration, compared to that produced by the ion generator when not in the box, is negligible. S1 is closed to use the generator in the non-operative mode. Ions produced by the generator then tend to be attracted to the ground wire, and repelled by the mesh which is now at the same potential as the discharge points. The ionization produced by the generator when used in this arrangement is virtually nil. This has been found to be a very effective means of disguising the generators (see Section 7-4). This is largely due to the fact that even when no ions are being emitted from the box the discharge points still produce the faint blue glow and hissing noise characteristic of corona discharge.

The reaction timer built for this project was closely based on a design by Ashley (1980). It is a compact, portable unit employing transistor-transistor logic, with the capacity to measure simple or choice reaction
FIGURE 7-1: Disguised negative ion generator
Figure 7-2 Disguised ion generator circuit
times with a precision of one millisecond.

A reaction time measurement is initiated by the subject pressing, and keeping depressed, switch SØ (see Figure 7-3). After a random time delay, ranging from zero to approximately five seconds, one of the light-emitting diodes (LED's) will be illuminated. If the timer is in choice reaction time mode this may be any one of L1 to L5, but in simple reaction time mode only L3 can light up. Switch S6 determines the mode of operation. The subject is to then press as quickly as possible one of switches S1 to S5, corresponding to the illuminated LED. The time between the illumination of a LED and the pressing of its switch is defined as the "reaction time", and this is displayed automatically. To prevent false times being accepted, an "error LED" will light up if i) SØ is released before one of L1 to L5 is illuminated, or ii) SØ and one or more of S1 to S5 are simultaneously depressed.

The circuit diagram of the reaction timer is shown in Figure 7-4. Three oscillators, consisting of IC6c,d,e, IC5c,d,e and IC5f with IC6a,b, are used to determine the random time delay and to clock the reaction time. The frequencies of these are 1.00 kHz ("slow"), ~2 kHz ("fast") and ~1 MHz ("very fast"), respectively. The NAND-gates IC9 and IC10a,b,c determine which oscillator provides pulses to the string of four decade dividers IC20 to IC23.
Initially the very fast oscillator is used as the clock, and the decade dividers count from 0 to 9999 about every 10 ms. When S₀ is pressed the clock is changed to the fast oscillator, which then completes the count back to zero. Depending on what the count was when S₀ was pressed this may take up to five seconds, and after this period one of L₁ to L₅ will be illuminated. This starts the measurement of reaction time by the slow oscillator, which is displayed by the four LT302 common anode 7-segment LED displays. When the correct switch (S₁ to S₅) is pressed the clock pulses are inhibited and the reaction time may be noted. IC₂₈ reduces the average segment current of the LT302's by supplying a 90% duty cycle square wave to the ripple blanking outputs of the decoder drivers IC₂₄ to IC₂₇.

The selection of which one of L₁ to L₅ will be illuminated is done by the 5-bit shift register IC₁₉ connected as a ring counter. The register is loaded with 00100 when S₀ is pressed but is then clocked from the slow oscillator. After the random time delay LED's L₁ to L₅ indicate the state of the register. To be used in simple reaction time mode switch S₆ is opened to disconnect the clock-pulse input to IC₁₉.

IC₁₀d, IC₁₁ and IC₁₃b determine whether either of the error conditions described above exist, and if so this is indicated by L₆ lighting up.

A power supply capable of supplying 5 V at 1A is necessary for the reaction timer. This was achieved
by use of a full-wave rectifier and a 7805 regulator. This regulator is very convenient as it employs internal current limiting and thermal shutdown, making it almost indestructible.

FIGURE 7-3: Reaction timer
FIGURE 7-4 Reaction timer circuit
Section 7-5: Results

The reaction times (in milliseconds) of the subjects in the preliminary experiment are given below. Each value is the mean of ten reaction time measurements. The tables are arranged according to time of day, whether the ionizer was active (A) or inactive (I), and whether it was the first (1) or second day (2) with an ionizer.

Table 7-1 Reaction Time Results (ms)

<table>
<thead>
<tr>
<th></th>
<th>FA</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
<td></td>
<td>Ionizer</td>
<td>Day</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td>466.6</td>
<td>435.2</td>
<td>414.0</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td>398.6</td>
<td>420.5</td>
<td>440.8</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
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<td>355.9</td>
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<td>378.0</td>
<td>369.0</td>
<td>403.8</td>
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</table>

<table>
<thead>
<tr>
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<th>Day</th>
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<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>A</td>
<td></td>
<td>391.7</td>
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<td>437.4</td>
<td></td>
<td>422.8</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>370.0</td>
<td></td>
<td>358.4</td>
<td></td>
<td>418.0</td>
</tr>
<tr>
<td>I</td>
<td></td>
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<td>365.2</td>
<td></td>
<td>405.8</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>398.2</td>
<td></td>
<td>454.5</td>
<td></td>
<td>391.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>534.2</td>
<td></td>
<td>561.0</td>
<td></td>
<td>515.8</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>585.9</td>
<td></td>
<td>587.4</td>
<td></td>
<td>586.6</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>603.5</td>
<td></td>
<td>570.3</td>
<td></td>
<td>624.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Day</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>596.3</td>
<td></td>
<td>544.9</td>
<td></td>
<td>578.7</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>534.2</td>
<td></td>
<td>561.0</td>
<td></td>
<td>515.8</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>585.9</td>
<td></td>
<td>587.4</td>
<td></td>
<td>586.6</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>603.5</td>
<td></td>
<td>570.3</td>
<td></td>
<td>624.3</td>
</tr>
</tbody>
</table>

Subject: TC
The small ion concentration, temperature and relative humidity in the subjects' offices are given below. The order in which they are given for each subject is chronological.

Subject: MM

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Day</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>605.5</td>
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<tr>
<td>I</td>
<td>1</td>
<td>582.0</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>562.0</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>591.4</td>
</tr>
</tbody>
</table>

Subject: SP

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Day</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>547.3</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>470.8</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>404.6</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>423.8</td>
</tr>
</tbody>
</table>
Table 7-2: Ion Concentration, Temperature and Relative Humidity

<table>
<thead>
<tr>
<th>Subject</th>
<th>Ionizer</th>
<th>Temp (°C)</th>
<th>Rel. Hum. (%)</th>
<th>n (ml⁻¹)⁻</th>
<th>n⁺ (ml⁻¹)⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA</td>
<td>active</td>
<td>21.0</td>
<td>38</td>
<td>37,000</td>
<td>0</td>
</tr>
<tr>
<td>FA</td>
<td>inactive</td>
<td>20.0</td>
<td>36</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>FA</td>
<td>inactive</td>
<td>19.0</td>
<td>46</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>FA</td>
<td>active</td>
<td>18.5</td>
<td>50</td>
<td>130,000</td>
<td>0</td>
</tr>
<tr>
<td>TC</td>
<td>inactive</td>
<td>20.5</td>
<td>37</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>TC</td>
<td>active</td>
<td>20.5</td>
<td>37</td>
<td>200,000</td>
<td>0</td>
</tr>
<tr>
<td>TC</td>
<td>active</td>
<td>18.5</td>
<td>50</td>
<td>240,000</td>
<td>0</td>
</tr>
<tr>
<td>TC</td>
<td>inactive</td>
<td>20.5</td>
<td>45</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>MM</td>
<td>active</td>
<td>21.5</td>
<td>62</td>
<td>210,000</td>
<td>0</td>
</tr>
<tr>
<td>MM</td>
<td>inactive</td>
<td>22.0</td>
<td>43</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>MM</td>
<td>inactive</td>
<td>23.0</td>
<td>41</td>
<td>200</td>
<td>220</td>
</tr>
<tr>
<td>MM</td>
<td>active</td>
<td>23.0</td>
<td>52</td>
<td>250,000</td>
<td>0</td>
</tr>
<tr>
<td>SP</td>
<td>active</td>
<td>21.5</td>
<td>56</td>
<td>240</td>
<td>360</td>
</tr>
<tr>
<td>SP</td>
<td>inactive</td>
<td>23.0</td>
<td>38</td>
<td>100,000</td>
<td>0</td>
</tr>
<tr>
<td>SP</td>
<td>inactive</td>
<td>23.0</td>
<td>38</td>
<td>110,000</td>
<td>0</td>
</tr>
<tr>
<td>SP</td>
<td>active</td>
<td>23.0</td>
<td>50</td>
<td>440</td>
<td>320</td>
</tr>
</tbody>
</table>

No subject said that they were currently on any drugs. Their opinions as to whether they thought their ionizer was working are summarized in Table 7-3.
Table 7-3: Responses to the Question "Did you think that the ion generator was working today?"

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Active ionizer</th>
<th>Inactive ionizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct response</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Incorrect response</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>&quot;Don't know&quot;</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Of the four times on which a subject believed that the ionizer was active, it was thought that it had a beneficial effect three times and no effect on the other occasion.

Section 7-6: Analysis and Conclusions

The mean reaction times, classified according to ionizer, day, time, and combinations of these, are summarized below. Days 1 and 2 refer to the first and second days on which the subject had a particular ionizer.

Table 7-4: Mean Reaction Time (ms)

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Day</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inactive</td>
<td>Active</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>505.7</td>
<td>500.4</td>
<td>514.9</td>
<td>419.2</td>
</tr>
<tr>
<td>Time</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>514.0</td>
<td>509.2</td>
<td>504.1</td>
<td>411.0</td>
</tr>
</tbody>
</table>
The statistical technique for determining whether the differences between the means are significant is the analysis of variance. The logic behind this analysis is that if every group of subjects comes from the same population (the "null hypothesis") then the between-
group estimate of population variance will be equal to
the within-group estimates of population variance. For
a given significance level the null hypothesis is
rejected if the ratio of the within-group variance to the
between-group variance (called the "variance ratio"
or "F") is greater than a critical value. A derivation
of this can be found in De Groot (1975).

The significance level is equal to the probability
that the difference between the means is due to chance.
When rejecting the null hypothesis, then, the significance
level reflects the confidence with which an independent
variable can be said to influence the dependent variable.
If the null hypothesis is rejected, but the independent
variable actually had no effect, then a Type 1 error
has been committed and the probability of this is equal
to the significance level. On the other hand a Type 2
error is committed if the null hypothesis is accepted
and the independent variable did have an effect. The
probability of this cannot be determined, but it
decreases as the real effect of the independent variable
increases.

A feature of the analysis of variance is that it
indicates whether the independent variables interact.
By interaction it is meant that the effect of one
variable depends on the level of the other. Note that
interaction effects are separate to the main effects
of the independent variables, and for an interaction
effect to be significant it is not necessary for any
of the main effects to be significant.

The data were analysed with the 'ANOVA' programme of the Genstat Statistics Package on the Australian National University's Univac computer. Note that the results given in Section 7-5 are the means of each set of ten reaction time measurements, but in the analysis of variance all individual measurements were used because this would be more sensitive to changes in performance.

Table 7-5: Analysis of Variance Table

<table>
<thead>
<tr>
<th>Source of variance</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionizer (I)</td>
<td>1</td>
<td>6 907</td>
<td>6 907</td>
<td>1.923</td>
<td>ns</td>
</tr>
<tr>
<td>Day (D)</td>
<td>1</td>
<td>135 256</td>
<td>135 256</td>
<td>37.659</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time (T)</td>
<td>5</td>
<td>90 482</td>
<td>18 096</td>
<td>5.039</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>I X D</td>
<td>1</td>
<td>4 204</td>
<td>4 204</td>
<td>1.171</td>
<td>ns</td>
</tr>
<tr>
<td>I X T</td>
<td>5</td>
<td>34 920</td>
<td>6 984</td>
<td>1.945</td>
<td>&lt;0.085</td>
</tr>
<tr>
<td>D X T</td>
<td>5</td>
<td>76 976</td>
<td>15 395</td>
<td>4.286</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>I X D X T</td>
<td>5</td>
<td>51 022</td>
<td>10 204</td>
<td>2.841</td>
<td>&lt;0.015</td>
</tr>
<tr>
<td>Residual</td>
<td>983</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both the time of day and which of the two days a subject had a particular ionizer influenced reaction time at a significance level of 0.1%. However, which ionizer was being used was not significant. Day and time had a highly significant interaction (0.1%) while other combinations of variables exhibited no significant interaction.
Table 7-3 indicates that the subjects could not tell whether their ionizer was in an active or inactive state. Only six of the sixteen opinions as to the operative state of the ionizer were correct and so the disguise of the ionizers was adequate.

The ion concentration produced by the active ionizer ranged from $37,000 \text{ ml}^{-1}$ to $250,000 \text{ ml}^{-1}$ with an average of $160,000 \text{ ml}^{-1}$. The lower limit resulted when the ionizer was placed directly behind a telephone. The metal dial on the face of this is grounded and acted as a sink for the ions. In all other cases a concentration of at least $100,000 \text{ ml}^{-1}$ was obtained. When the inactive ionizer was used the ion concentration did not rise above ambient level.

While temperature and humidity were not being controlled they were measured to check that no subject experienced extremes in these parameters. The largest range in noon temperature was only $2.5° (18.5°$ to $21.0°C)$ and relative humidity varies by at most $21\%$ (from $41\%$ to $62\%$).

With the limited scope of this preliminary work it is not possible to draw firm conclusions about the effect of negative air ions. The experimental design, however, can be assessed. One deficiency with it is that the subjects do not perform the reaction tests in a control environment i.e. one in which no ionizer is present. This would allow a comparison between performance under control and experimental conditions. Also, having each subject experience
experimental condition on two days introduces possible interaction effects which complicate analysis and interpretation of results. It would be preferable to have each condition for only one day with the order of conditions randomized to account for the transfer effects of practice and fatigue.

The basic aim of this research was discussed in detail in Chapter 7. It is worthwhile, however, to reiterate the major points.

Air ionization has been shown to influence psycho-motor performance under controlled laboratory conditions, but no research has been done on whether this is also the case in a work environment. The present experiment was designed to study the effect of negative air ions on human reaction time in a typical office situation.

Subjects were to be tested in their own office under three ionization conditions: with an active ion generator installed in the office, with a disabled ion generator (disguised to appear to be operating normally) installed, and with no generator installed. To extract the influence of the circadian rhythm of performance, the tests were to be repeated several times throughout the day.

Apart from the level of air ionization no controls were to be placed on the environment. Temperature and humidity are known to affect human performance and so these parameters were monitored to check that extreme values did confound the results. In order that the
CHAPTER 8:

MAIN EXPERIMENT

Section 8-1: Aim

The basic aim of this research was discussed in detail in Chapter 7. It is worthwhile, however, to reiterate the major points.

Air ionization has been shown to influence psychomotor performance under controlled laboratory conditions, but no research had been done on whether this is also the case in a work environment. The present experiment was designed to study the effect of negative air ions on human reaction time in a typical office situation.

Subjects were to be tested in their own office under three ionization conditions - with an active ion generator installed in the office, with a disabled ion generator (disguised to appear to be operating normally) installed, and with no generator installed. To extract the influence of the circadian rhythm of performance the tests were to be repeated several times throughout the day.

Apart from the level of air ionization no controls were to be placed on the environment. Temperature and humidity are known to affect human performance and so these parameters were monitored to check that extreme values did confound the results. In order that the
subjects be free to go about their work no earth-straps were attached to them.

Any statistically significant difference in reaction time in the subjects when tested under the various ionization conditions should be attributable to the effect of the air ions on human performance. Interaction effects between ionization and circadian rhythm might also be present and should be considered in the analysis.

Section 8-2: Method

Volunteers for this experiment were called for from the secretaries of the Faculty of Science at the Australian National University. Thirteen agreed to participate, and for the reasons outlined in Section 7-3 the purpose of the research was explained to them.

The reaction timer described in Section 7-4 was used in this experiment, in the "choice reaction time mode". All subjects were allowed a practice session with the timer before the commencement of the experiment so that they would be familiar with its operation. This is to minimise the effect of practice throughout the experiment.

As in the preliminary trial each subject had her reaction time measured ten times in succession in her office at 10 a.m., 11 a.m., 12 noon, 2 p.m., 3 p.m. and 4 p.m. This was done on three consecutive working days.
On two of these days an ionizer was installed in the office at 9 a.m. and was active on one of these days and inactive on the other. Stevens (1982) method was used to disguise the operative state of the ionizers (Section 7-4). The ionizer was placed about a metre from the subject's usual working position. It was desired to create a negative ion concentration of at least 100,000 ml\(^{-1}\) near the subject when the ionizer was active. On the third day no ionizer was installed i.e. the subject was in control conditions.

Note that the order in which a subject experienced the ionization conditions was randomized. This counterbalancing was to account for transfer effects. Because of the double-blind nature of the experiment an assistant chose the order of conditions for each subject.

After the noon tests an assistant measured the small ion concentration and ambient temperature and relative humidity in the subject's office.

At the end of the day's tests each subject was asked:

i) Are you currently taking any medication or drugs?

ii) Did you think that the ion generator was working today?

iii) If so, did you think that it had a detrimental effect/a beneficial effect/no effect?

On a given day sometimes more than one subject was involved with the experiment. If two or three subjects had offices very close together they would have their reaction time tests in succession. This enabled the experiment to be concluded in as short a time as practicable.
Section 8-3: Results

The experiment was conducted from 4/8/81 to 22/9/81 inclusive. The results for individual subjects are tabulated below, and consist of the average of each set of ten reaction time measurements. The three ionization conditions were

i) "active" - an operative ionizer was installed
ii) "inactive" - a disabled ionizer was installed
iii) "control" - no ionizer was installed.

Table 8-1: Reaction Time Results (ms)

<table>
<thead>
<tr>
<th>Ionization</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>active</td>
<td>361.5</td>
</tr>
<tr>
<td>inactive</td>
<td>401.6</td>
</tr>
<tr>
<td>control</td>
<td>350.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ionization</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>active</td>
<td>565.3</td>
</tr>
<tr>
<td>inactive</td>
<td>552.2</td>
</tr>
<tr>
<td>control</td>
<td>551.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ionization</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>active</td>
<td>396.1</td>
</tr>
<tr>
<td>inactive</td>
<td>445.3</td>
</tr>
<tr>
<td>control</td>
<td>391.0</td>
</tr>
</tbody>
</table>
### Subject 4

<table>
<thead>
<tr>
<th>Ionization</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>471.3</td>
<td>458.2</td>
<td>439.4</td>
<td>458.2</td>
<td>431.0</td>
<td>425.7</td>
</tr>
<tr>
<td>inactive</td>
<td>501.7</td>
<td>508.4</td>
<td>485.5</td>
<td>483.3</td>
<td>458.8</td>
<td>459.2</td>
</tr>
<tr>
<td>control</td>
<td>427.5</td>
<td>402.5</td>
<td>404.5</td>
<td>403.2</td>
<td>420.2</td>
<td>419.9</td>
</tr>
</tbody>
</table>

### Subject 5

<table>
<thead>
<tr>
<th>Ionization</th>
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<th>11</th>
<th>12</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>399.3</td>
<td>395.3</td>
<td>404.9</td>
<td>380.2</td>
<td>423.2</td>
<td>396.1</td>
</tr>
<tr>
<td>inactive</td>
<td>375.8</td>
<td>398.9</td>
<td>392.1</td>
<td>390.6</td>
<td>377.5</td>
<td>355.1</td>
</tr>
<tr>
<td>control</td>
<td>374.8</td>
<td>383.7</td>
<td>376.7</td>
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<td>383.6</td>
<td>404.1</td>
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Subject 13

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<td>628.7</td>
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<td>656.3</td>
<td>668.8</td>
<td>667.7</td>
<td>689.3</td>
</tr>
</tbody>
</table>

The results of the measurements of the noon temperature, relative humidity and small air ion concentration are given below.

Table 8-2: Environmental Conditions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Ionizer</th>
<th>Temp (°C)</th>
<th>Rel. Hum. (%)</th>
<th>n^−(ml⁻¹)</th>
<th>n^+ (ml⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>active</td>
<td>19.5</td>
<td>47</td>
<td>200,000</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>inactive</td>
<td>19.0</td>
<td>46</td>
<td>200</td>
<td>240</td>
</tr>
<tr>
<td>1</td>
<td>control</td>
<td>19.0</td>
<td>38</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>active</td>
<td>22.5</td>
<td>41</td>
<td>220,000</td>
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<td>480</td>
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<tr>
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<td>control</td>
<td>21.5</td>
<td>39</td>
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<td>500</td>
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<tr>
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<tr>
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<tr>
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<td>38</td>
<td>60</td>
<td>100</td>
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</tbody>
</table>
FIGURE 8-1: The author conducting a reaction time test
<table>
<thead>
<tr>
<th>Subject</th>
<th>Ionizer</th>
<th>Temp (°C)</th>
<th>Rel. Hum. (%)</th>
<th>$n^-(\text{ml}^{-1})$</th>
<th>$n^+(\text{ml}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
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<tr>
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<td>49</td>
<td>400</td>
<td>400</td>
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<td>Rel. Hum. (%)</td>
<td>n⁻ (ml⁻¹)</td>
<td>n⁺ (ml⁻¹)</td>
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<td>190,000</td>
<td>0</td>
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<td>24.0</td>
<td>33</td>
<td>400</td>
<td>400</td>
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<td>34</td>
<td>100,000</td>
<td>0</td>
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<tr>
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<td>39</td>
<td>360</td>
<td>480</td>
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<tr>
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<td>400</td>
<td>440</td>
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<tr>
<td>12</td>
<td>active</td>
<td>18.0</td>
<td>49</td>
<td>150,000</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>inactive</td>
<td>18.5</td>
<td>41</td>
<td>200</td>
<td>360</td>
</tr>
<tr>
<td>12</td>
<td>control</td>
<td>19.5</td>
<td>47</td>
<td>600</td>
<td>640</td>
</tr>
</tbody>
</table>
Table 8-3: Responses to the question "Did you think your ion generator was working today?"

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Correct</th>
<th>Incorrect</th>
<th>&quot;Don't know&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>2</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>inactive</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

Of the six subjects who believed that their ionizer was active three thought that it had a beneficial effect on them and three thought that it had no effect.

No subject said that they took any drugs during the period of the experiment.
Before the differences in reaction time are statistically analyzed it must be established that the results were not influenced by external factors. In the present case the possible effects of i) extreme values of temperature or humidity or ii) subjects being able to distinguish the active and inactive generators should be investigated.

Table 8-2 shows that the ambient noon temperature and humidity in the subjects' offices was very steady over the period each subject was involved in the test. The maximum variation in temperature for a subject was 2.5°C, while relative humidity had at most an 11% variation. There was, of course, a larger difference in conditions between offices. Noon temperatures ranged from 18.0°C to 25.0°C and relative humidity from 32% to 58%. Table 9-1 summarises these measurements.

Table 9-1: Temperature and Relative Humidity

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Mean Temp. (Range) [°C]</th>
<th>Mean Rel. Hum. (Range) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>22.0 (19.0 - 25.0)</td>
<td>43 (32 - 53)</td>
</tr>
<tr>
<td>inactive</td>
<td>22.0 (18.5 - 24.5)</td>
<td>44 (33 - 58)</td>
</tr>
<tr>
<td>control</td>
<td>22.0 (18.0 - 25.0)</td>
<td>43 (32 - 58)</td>
</tr>
</tbody>
</table>

Since the climate was so constant between the
ionization levels this would not have systematically influenced subject performance.

The maximum, minimum and average positive and negative small ion concentration for the three ionization conditions are shown below.

Table 9-2: Small Ion Concentration

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>$n_{\text{min}}^{-}(\text{ml}^{-1})$</th>
<th>$n_{\text{max}}^{-}(\text{ml}^{-1})$</th>
<th>$n_{\text{ave}}^{-}(\text{ml}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>100,000</td>
<td>250,000</td>
<td>180,000</td>
</tr>
<tr>
<td>inactive</td>
<td>100</td>
<td>400</td>
<td>230</td>
</tr>
<tr>
<td>control</td>
<td>60</td>
<td>600</td>
<td>370</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>$n_{\text{min}}^{+}(\text{ml}^{-1})$</th>
<th>$n_{\text{max}}^{+}(\text{ml}^{-1})$</th>
<th>$n_{\text{ave}}^{+}(\text{ml}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>inactive</td>
<td>100</td>
<td>480</td>
<td>270</td>
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<tr>
<td>control</td>
<td>100</td>
<td>680</td>
<td>470</td>
</tr>
</tbody>
</table>

Despite the vast difference in ion concentration in the vicinity of an active or inactive ionizer subjects showed no ability to distinguish between them. Table 8-3 shows that in half of the cases they had no idea as to the operative state of the ionizer, and when they did offer an opinion it was correct only about a third of the time. This indicates that the method used to disguise the ionizers was very effective.

With these two possible effects on performance dismissed it is now possible to attribute changes in
reaction time to either the level of ionization or the
time of day. The results for individual subjects were
not analyzed because i) reaction time varies widely
between different subjects and for the same subject at
different times, and ii) with this experimental design
it is not possible to correct for transfer effects in
an individual. Instead, the combined results of the whole
series of experiments were statistically analysed using
a two-way analysis of variance.

However, when an analysis of variance is performed
two assumptions are made about the distribution of the
data:- that the sample variances are homogeneous and
that the sample distributions are normal.

Within-group variances are expected to be fairly
constant and independent of the level of treatment.
However, if manipulation of an independent variable
influences the within-group variance more than would be
expected on the basis of chance fluctuations then
homogeneity of variance has been violated. This can be
tested for by finding the $F_{\text{max}}$ value, which is the ratio
of the variance of the group having the largest variance
to that of the group having the smallest variance. For
a given level of significance $F_{\text{max}}$ must be less than a
critical value to conclude that the variances are homo-
genous.

The variance of the reaction time distributions
classified by ionization and time of day are listed
below.
### Table 9-2a: Variance of Reaction Time Distributions [(ms)²]

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Active</th>
<th>Inactive</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7539</td>
<td>8999</td>
<td>9522</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
<tr>
<td>9467</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ionizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
</tr>
<tr>
<td>Inactive</td>
</tr>
<tr>
<td>Control</td>
</tr>
</tbody>
</table>

An \( F_{\text{max}} \) value is necessary for all three types of distributions. These values are:

- ionization: \( F_{\text{max}} = 1.26 \)
- time: \( F_{\text{max}} = 1.18 \)
- ionization x time: \( F_{\text{max}} = 1.82 \)

Comparison of these values with the appropriate critical value (Wood, 1974) shows that all of the sample distributions have variances which are homogeneous at the 5% level of significance.
The analysis of variance is insensitive with respect to violations of the assumption of normality of sample distributions. However, gross departures from normality should be checked for. An indication of deviation of normality is given by the values of skewness and kurtosis. Skewness is a measure of the symmetry of the distribution while kurtosis indicates the tails of the distribution. These parameters are defined as follows:

Consider a data distribution and data points $x_1, x_2, \ldots, x_n$. The first moment, or mean, is given by

$$m_1 = \frac{1}{n} \sum_{i=1}^{n} x_i$$

The second moment, or variance, is given by

$$m_2 = \frac{1}{n} \sum_{i=1}^{n} (x_i - m_1)^2$$

Similarly, the third and fourth moments of the distribution are defined by

$$m_3 = \frac{1}{n} \sum_{i=1}^{n} (x_i - m_1)^3$$

$$m_4 = \frac{1}{n} \sum_{i=1}^{n} (x_i - m_1)^4$$

Skewness and kurtosis can then be defined in terms of these moments:

Skewness: $Sk = m_3 / m_2^{3/2}$

Kurtosis: $K = m_4 / m_2^2$

Figure 9-1: Mean reaction time

control conditions
inactive ionizer
active ionizer

![Graph showing mean reaction time]
The analysis of variance is insensitive with respect to violations of the assumption of normality of sample distributions. However, gross departures from normality should be checked for. An indication of the degree of normality is given by the values of skewness and kurtosis. Skewness is a measure of the symmetry of the distribution while kurtosis indicates the flatness or peakedness of the distribution. These parameters are defined as follows:

Consider a sample distribution with $N$ data points $(x_1, x_2, \ldots, x_N)$. The first moment, or mean, is given by

$$
\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i
$$

(9.1)

The second moment, or variance, is given by

$$
m_2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2
$$

(9.2)

Similarly, the third and fourth moments of the distribution are defined by

$$
m_3 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^3
$$

(9.3)

$$
m_4 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^4
$$

(9.4)

Skewness and kurtosis can then be defined in terms of these moments:

$$
\text{skewness} = \frac{m_3}{(m_2)^{3/2}}
$$

(9.5)
A computer programme was written in FORTRAN by the author to calculate the skewness and kurtosis of the distribution curves. The results are listed below in Table 9-3.

Table 9-3: Skewness and Kurtosis of Reaction Time Distribution Curves

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>0.86</td>
<td>3.9</td>
</tr>
<tr>
<td>inactive</td>
<td>0.96</td>
<td>3.9</td>
</tr>
<tr>
<td>control</td>
<td>1.07</td>
<td>4.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 a.m.</td>
<td>0.96</td>
<td>4.4</td>
</tr>
<tr>
<td>11 a.m.</td>
<td>1.14</td>
<td>4.4</td>
</tr>
<tr>
<td>12 noon</td>
<td>0.91</td>
<td>5.0</td>
</tr>
<tr>
<td>2 p.m.</td>
<td>0.78</td>
<td>3.2</td>
</tr>
<tr>
<td>3 p.m.</td>
<td>0.90</td>
<td>3.7</td>
</tr>
<tr>
<td>4 p.m.</td>
<td>1.17</td>
<td>5.0</td>
</tr>
</tbody>
</table>

All of the distributions are skewed positive, i.e. have extreme scores above the mean. This is because some subjects may have very slow reactions but there is a practical lower limit to how quickly a person can react.
However, none of the values for skewness or kurtosis are extreme, and these distributions are therefore sufficiently close to normality to be used in an analysis of variance.

Mean reaction time, classified by which ionizer was in use and by time of day are summarised below.

**Table 9-4: Mean Reaction Time (ms)**

<table>
<thead>
<tr>
<th>Ionizer</th>
<th>Active</th>
<th>Inactive</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>456.2</td>
<td>466.0</td>
<td>457.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>466.8</td>
<td>460.7</td>
<td>461.7</td>
<td>462.8</td>
<td>454.6</td>
<td>453.5</td>
</tr>
</tbody>
</table>

These values are plotted in Figure 9-1. It is particularly interesting to note the difference in performance in subjects between when they were tested...
in control conditions and when they were tested with the inactive ionizer installed. It would be expected that reaction times in these two conditions would be very similar since they were, physically, virtually the same.

This was investigated with the 'ANOVA' programme of the Genstat Statistics Package to see if the differences are statistically significant.

Table 9-5: Analysis of Variance Control vs. Inactive Ionizer

<table>
<thead>
<tr>
<th>Source of Variance</th>
<th>df</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization (I)</td>
<td>1</td>
<td>26 224</td>
<td>26 224</td>
<td>8.645</td>
<td>0.005</td>
</tr>
<tr>
<td>Time (T)</td>
<td>5</td>
<td>38 949</td>
<td>7 790</td>
<td>2.568</td>
<td>0.05</td>
</tr>
<tr>
<td>I x T</td>
<td>5</td>
<td>19 665</td>
<td>3 933</td>
<td>1.297</td>
<td>ns</td>
</tr>
<tr>
<td>Residual</td>
<td>1536</td>
<td>4659 342</td>
<td>3 033</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This shows that there was a highly significant (0.5%) difference between performance in each of these conditions. This effect must be psychological, and not physiological, in nature because of the close similarity of the two environments. That is, the mere act of placing ionizer in a subject's office is sufficient to induce a change in reaction time.

If the level of air ionization also influences reaction time it will be independent of this placebo effect and must be looked for separately. Because the active and inactive ionizers were shown to be indistinguishable the results
obtained with these can be compared directly. Figure 9-1 shows the mean reaction time with the inactive ionizer to be longer than that with the active ionizer at all times of the day. The relative difference between them is given by, in an obvious notation, \((\text{RT inactive} - \text{RT active})/\text{RT inactive}\) and is listed in Table 9-6 for each time of day.

<table>
<thead>
<tr>
<th>Table 9-6: Relative Difference in Reaction Time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Ionizer vs. Inactive Ionizer</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>4.2</td>
</tr>
</tbody>
</table>

The overall difference is 2.1%, but is greater in the 10 a.m. and 4 p.m. sessions. Again the statistical significance of these results was checked with analysis of variance.

<table>
<thead>
<tr>
<th>Table 9-7: Analysis of Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Ionizer vs. Inactive Ionizer</td>
</tr>
<tr>
<td>Source of Variance</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Ionizer (I)</td>
</tr>
<tr>
<td>Time (T)</td>
</tr>
<tr>
<td>I x T</td>
</tr>
<tr>
<td>Residual</td>
</tr>
</tbody>
</table>
This analysis indicates that the difference between performance in these two ionization conditions is a genuine effect, as the significance level of 0.1% means that the probability of this difference being a statistical fluctuation is less than one in a thousand.

It is not the purpose of this research to examine the biological mechanism by which air ionization influences human reaction time. The biological activity of air ions has, however, been linked with serotonin. This neurohormone, also known as 5-hydroxytryptamine or 5-HT, is involved in the transmission of nerve impulses and is found in blood and in high concentrations in the lower midbrain. It is known to effect sleep patterns and mood, and elevated levels of serotonin have been observed to cause headache, nausea, diarrhea and vomiting (Giannini, 1978-79).

Krueger and Smith (1960) found that positive air ions tend to raise blood levels of serotonin and negative ions tend to lower them in rabbits, mice, rats, guinea pigs and monkeys. Their postulated mechanism for the effects of ions on serotonin is outlined in Figure 9-2.

More recent work has been conducted by Sulman, Levy, Lunkan, Pfeifer and Tal (1978) on human subjects. They found that negative ions decreased urinary excretion of serotonin, 5-hydroxyindoleacetic and (5-HIAA) histamine and thyroxine. It also improved electroencephalograms (EEG) by stabilising frequency, increasing amplitude, spreading brainwaves from the occipital to the frontal
area and synchronising the hemisphere tracings. They concluded that this causes "improved performance" and this may explain the decrease in reaction time produced by negative ions.

It may seem unlikely at first that air ions, which make up such a minute fraction of the air we breathe, can be biologically active. There are, however, precedents in nature where small stimuli produce observable effects. One of these is that male silkworms can react to fewer than two hundred molecules of female silkworm sex attractant per millilitre (Bossert and Wilson 1963). Another is that a flash of light can be perceived when a single photon of appropriate frequency strikes the human retina (Pirenne, 1958).

Psychomotor performance is known to have a circadian rhythm and therefore it is not surprising that reaction time is dependent on time. There was, however, no significant interaction between time of day and ionization. Hawkins and Barker found such an interaction to be highly significant, and concluded that air ionization influences the circadian rhythm. Their measurements were made from 9 a.m. to 9 p.m. and they found that subjects in control conditions had a steady decline in performance between 4 p.m. and 9 p.m., while those in a negatively-ionized atmosphere "maintained a high level of performance throughout ... the evening". The present experiment was conducted over a more limited time scale, 10 a.m. to 4 p.m. and this is possibly why a similar interaction was not observed.
CHAPTER 10

CONCLUSIONS

The role of air ions as part of our physical environment was investigated. In particular, research was conducted on the influence of negative small air ions on reaction time in a work situation.

The results of this series of experiments indicate that air ions can effect reaction time. When the negative ion concentration in thirteen secretarial offices was raised from ambient levels of a few hundred ions per millilitre to around one hundred and fifty thousand ions per millilitre and the subjects exposed to this for the duration of working day visual reaction time decreased by an average of 2.1%. This is much smaller than the 6.1% decrease previously found in the laboratory situation. The maximum observed changes were a 6.8% increase and an 11.3% decrease in reaction time.

The overall improvement in performance, albeit a relatively small one was highly statistically significant. Analysis of variance showed that there was less than one chance in a thousand of it being due to chance alone. The placement of inactive ionizers in the offices had a placebo effect on performance but the experimental design was such that this could be isolated from the physiological effect of ions.
Reactions were also shown to be dependent on the time of day but no significant interaction was found between time and the level of ionization.

The importance of these results lies in the fact that they were obtained in a typical work situation. Previous research in this field was conducted in the laboratory with conditions very different to those usually encountered in day-to-day life. Particularly notable is the fact that the benefit of negative ions can be obtained without the subjects being earthed, because if this were not the case the practical usefulness of negative air ionization would be seriously reduced.

Indoor ion concentration is generally lower than that outdoors, and this is accentuated by poorly designed air-conditioning. Furthermore, the presence of people in an office has been shown by others to i) increase the concentration of large ions and decrease that of small ions, and ii) increase the ratio \( n^+/n^- \). In these situations the installation of negative air ion generators would be expected to improve the psychomotor performance of at least some people.

Work needs to be done to determine the optimum ion concentration. This could initially be approached purely empirically. Clearly, however, if the influence of air ions on human performance is to be fully appreciated the mechanism by which they act needs to be ascertained. In addition to this, all of the species
of air ions need to be determined and it must be established whether the relative abundances of the species are dependent on the means of ionization. It may then be possible to design ion generators to produce the optimum type and concentration of air ions. These must remain long-term aims because of substantial experimental difficulties in the way.

In the short term, ways of arranging office routine and placement of office furniture to maximise the ion effect should be sought out and implemented where possible.
PART B

Radioucides have been used in medicine for about four decades. In the 1940’s the differential uptake of I-131 and P-32 was employed in therapy and diagnosis, with the Geiger counter being the main radiation detector. The introduction of scintillation counters in the following decade allowed imaging to be done. Also around this time the techniques of tagging biological compounds with radiounicles, e.g. Cr-51 labelled red blood cells and Co-60 labelled vitamin B12, were developed.

During the 1960’s automatic rectilinear scanners became available which allowed the distribution of a radionuclide in an organ, or indeed the entire body, to be imaged routinely. This period also saw the development of in vitro laboratory tests with radinuclides such as radioactive serotonin. The gamma camera, which was originally designed by H.G. Anger in the mid-1940’s, was refined throughout the 1950’s to such an extent that it has made the rectilinear scanner obsolete. Most large hospitals now have a Department of Nuclear Medicine, the operation of which centres around one or more gamma cameras.

In this project the principles of image formation with a gamma camera were studied. The particular case of imaging with the radionuclide gallium-67 was then
INTRODUCTION

Radionuclides have been used in medicine for about four decades. In the 1940's the differential uptake of I-131 and P-32 was employed in therapy and diagnosis, with the Geiger counter being the main radiation detector. The introduction of scintillation counters in the following decade allowed some manual scanning to be done. Also around this time the techniques of tagging biological compounds with radionuclides, e.g. Cr-51 labelled red blood cells and Co-60 labelled vitamin B₁₂, were developed. During the 1960's automatic rectilinear scanners became available which allowed the distribution of a radionuclide in an organ, or indeed the entire body, to be imaged routinely. This period also saw the development of in vitro laboratory tests with radionuclides, such as radioimmunoassays. The gamma camera, which was originally designed by H.O. Anger in the mid-1960's, was refined throughout the 1970's to such an extent that it has made the rectilinear scanner obsolete. Most large hospitals now have a Department of Nuclear Medicine, the operation of which centres around one or more gamma cameras.

In this project the principles of image formation with a gamma camera were studied. The particular case of imaging with the radionuclide gallium-67 was then
investigated. As discussed in Chapter 15, the relative complexity of its spectrum has meant that no standard set of imaging parameters has been accepted by the Nuclear Medicine community. The main aim of the present research was to determine what combination of collimator and analyzer energy window(s) would give the optimum blend of system resolution and sensitivity.

This was achieved by firstly generating Ga-67 spectra with different collimators to compare their effects on spectra measured under scatter-free and simulated in vivo conditions. A system was then developed which quantified the measurement of camera resolution and sensitivity, and this was used to calculate these parameters over a range of collimators and energy windows. Based on these results, the optimum collimator and energy windows for use in Ga-67 imaging were determined.

In order to put this work in its clinical context a brief review is given of the clinical use of Ga-67 scans and of the mechanisms of its localization in the human body.
CHAPTER 12

CLINICAL USES OF GALLIUM-67 IMAGING IN NUCLEAR MEDICINE

Section 12-1 Management of Patients with Malignant Lymphoma

When Edwards and Hayes (1969, 1970) reported the use of Ga-67 imaging to detect tumours a great deal of excitement was generated over the potential of this new tumour scanning agent. In the following years, however, it was found that this technique is limited in that gallium citrate not only localizes in neoplastic tissue but also in inflamed tissue and some normal organs. This means that a biopsy is often necessary to confirm the presence of a tumour if a Ga-67 scan is positive. In spite of this Ga-67 has been found to be very useful in the clinical management of patients with malignant lymphoma.

An indication of the detectability of lymphoma by Ga-67 imaging is given by the sensitivity and specificity of the technique, defined as:

\[
\text{specificity} = \frac{\text{number of normal sites with negative tests}}{\text{total number of normal sites}}
\]

(12.1)

\[
\text{sensitivity} = \frac{\text{number of abnormal sites with positive tests}}{\text{total number of abnormal sites}}
\]

(12.2)

Turner, Fordham, Ali and Slayton (1978) reviewed the
literature and found that specificity ranged from 87% to 100% while sensitivity was between 25% and 78%. Sensitivity is lower than one would wish, but this is mainly due to criteria being set that minimize the false positive rate of scan interpretation.

The detectability of lymphoma has been found to vary with tumour histology. Horn, Ray and Kriss (1976) found that the sensitivity of Ga-67 scanning is greater for sites of Hodgkin's disease or histiocytic lymphoma than for sites of lymphocytic lymphoma.

Some normal organs also take up Ga-67 and this means that detectability of lymphoma also varies with anatomical site. The normal accumulation of Ga-67 in the liver, for example, makes detection of lesions in that region difficult to detect. Also, activity accumulation in the cecum and sigmoid colon makes it difficult to interpret Ga-67 uptake in the iliac node regions. In general, superficial lesions are more easily detected than those deep in the abdomen.

A diagnosis of lymphoma cannot be made solely on the result of Ga-67 scans because of the localization of gallium in all types of pathologic tissue. An example of this is shown in Figure 12-1 which is a series of Ga-67 scans on a 35 year old male. Despite the high uptake of Ga-67 indicating the possible presence of lymphoma, laparotomy found the condition to actually be a benign perforated gastric ulcer. (Scans shown in this section are from Turner, et. al.)
Figure 12-1: Ga-67 scan of benign gastric ulcer - see text.
1978). A scan may, however, be able to identify possible sites for biopsy in cases where lymphoma is suspected but no easily accessible lymph nodes are enlarged.

The anatomical distribution, or "stage", of malignant lymphomas must be known in order to plan the most effective radio- or chemotherapy. If lymphoma has been histologically diagnosed Ga-67 scanning may play a role in the staging of the disease. This is normally done in conjunction with other tests, including physical examination, radiographs of the chest, bone marrow biopsy, needle biopsy of the liver and staging laparotomy (i.e. determination of the stage of the disease by surgical examination). Figure 12-2a shows the Ga-67 scans of a 12 year old boy known to have lymphoma in the right neck. The scans showed that the disease had spread to below the diaphragm.

Ga-67 scanning is most useful for following the course of lymphoma after a patient has undergone therapy because of its simplicity and that it is non-invasive. Henkin, Poleyn and Quinn (1974) report that a positive Ga-67 scan may be the first, or indeed the only, objective evidence of the recurrence or persistence of the disease. The change in gallium uptake after therapy has been suggested as an index of the response of the tumour to therapy, but Andrews and Edwards (1975) point out that the rate of gallium uptake may be decreased during or shortly after therapy,
Figure 12-2: Histiocytic lymphoma a) before and b) after chemotherapy
making the use of such an index doubtful. Post-therapy positive scans are usually found to be more reliable than negative ones. An example of the latter is shown in Figure 12-2b. These scans show the same patient as in Figure 12-2a, but fourteen months later. In this case the tumour has responded well to chemotherapy.

Section 12-2 Detection of Inflammatory Disease

As mentioned in the previous section Ga-67 is taken up by inflammatory lesions and certain normal organs, and this property is now used in the detection of inflammatory disease by Ga-67 scanning. The standard adult intravenous dose is 40 to 50 uCi/kg (Staab and McCartney 1978), with smaller doses being used in children. If the patient is known to have a malignancy up to 10mCi total dose may be used to improve the image quality.

Table 12-1 lists the absorbed dose for selected organs (MIRD/Dose Estimate Report 2, 1973).

Table 12-1: Estimated Absorbed Dose

<table>
<thead>
<tr>
<th>Organ</th>
<th>Dose (Rad/mCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Intestine</td>
<td>2.0</td>
</tr>
<tr>
<td>Liver</td>
<td>0.5</td>
</tr>
<tr>
<td>Kidney</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Inflammatory disease may take up sufficient gallium in four to six hours to be identifiable. However, if this scan is negative further studies should be done a day or two later.

Normal gallium images show significant uptake in the liver, kidneys, spleen, epiphyseal regions of long bones, nasopharynx and colon (Carson, Milder and Johnston, 1973). Lactating breasts and overactive exocrine glands are areas of physiological uptake. Figure 12-3 shows three normal 48 hour gallium-67 images of a 35 year old female: a) anterior chest - normal bone and bilateral breast uptake, b) anterior abdomen and pelvis - normal liver accumulation without significant bowel gallium, and c) posterior abdomen - absence of renal uptake at 48 hours. (All scans in this Section are from Staab and McCartney, 1978).

Septic joints may be imaged with Ga-67, but by also imaging the joint with Tc-99m phosphate the septic focus may be more precisely localized. Figure 12-4 shows two such scans of the ulcerated heels of a patient with active osteomyelitis. In septic arthritis only gallium builds up in the synovium; Figure 12-5 is a 48 hour Ga-67 scan of a patient with this condition in the left knee.
Figure 12-3  Normal 48 hour Ga-67 scans

- see text
Figure 12-4: Scans of active osteomyelitis using a) Tc-99m phosphate, and b) Ga-67 (48 hr)

Figure 12-5: Synovial inflammation - see text
Gallium is taken up in the lungs in several pulmonary diseases, including pneumonia, tuberculosis, sarcoidosis and other interstitial diseases. Figure 12-6 shows the focal areas of uptake in a 72 hour scan of a patient with pneumonia.

Gallium-67 imaging is very useful in the case of patients having fevers of unknown origin. While viral illness and drug reactions account for most of these patients, some will have focal inflammatory lesions and others may have an underlying malignancy. Many of these localized causes can be identified on a gallium scan, and clinicians are tending to request these scans early in the evaluation of patients in this category.
Figure 12-6: Pneumonia - 72 hour Ga-67 scan
CHAPTER 13

MECHANISMS OF GALLIUM LOCALIZATION

Brucer, Andrews and Bruner (1953) first used radio­nuclides of gallium for radiation therapy of bone tumours. This work did not achieve its primary purpose, but the uptake of gallium in bone meant that Ga-67 was very useful as a bone-scanning agent. It was while scanning the bones of a patient with Hodgkins disease that Edwards and Hayes (1969,1970) observed that Ga-citrate localized in non-osseous tumours. Since that time Ga-67 has been widely used in imaging a variety of neo­plasms. The mechanism by which Ga-67 is localized in tumours, however, is still poorly understood.

Gallium-67 is given in the form of gallium citrate and is administered intravenously because it is poorly absorbed after oral, subcutaneous or intramuscular administration. During the first day after injection about 15 to 25% of the Ga-67 is excreted by the kidneys. Clearance after this time is slower, and over a week about 10% of the dose is excreted in the stool (Edwards, Hayes, Nelson, et al., 1970).

Nelson, et al. (1972) studied the organ distribution of gallium in patients who died two to three days after being injected with Ga-67. They found that the highest concentrations, in terms of percentage of injected dose, to be in the liver (5%), kidney (2%), spleen (1%) and
the skeleton including marrow (24%). Little gallium was retained in muscle, skin, blood, brain and fatty tissue. Localization within organs is not uniform. In the kidneys there is increased uptake in the cortex, the phagocytic cells of the spleen accumulate gallium, and in the liver Kupffer cells and hepatocytes show selective localization. Of the gallium absorbed into the blood, about 30% binds to the plasma proteins transferrin and heptoglobin (Hartman and Hayes, 1969), and is also bound loosely to albumin and globulins.

The localization of gallium in normal tissue can be explained by the migration of Ga-67 from transferrin to the secretory protein lactoferrin. Lactoferrin, with a molecular weight of approximately eighty thousand, has a similar configuration to transferrin. It is however, capable of attracting gallium away from transferrin, especially in an acidic environment. Lactoferrin is present in relatively high concentrations in tissues in which gallium localizes, and both transferrin and lactoferrin are metabolized in the liver. This provides an explanation of the normal pattern of gallium uptake.

The uptake of gallium is not uniform between tumours of different types, and has been observed to be highest in osteosarcomas, lymphomas, lung cancer, melanoma and breast cancer (Nelson, et al. 1972, Milder, Frankel, Bulkley, et al., 1973). The reasons for its high concentrations in some tumours and not others are
unknown but some observations on the factors influencing gallium uptake are summarized below.

i) Some tumours show a correlation between growth rate and gallium uptake, but others do not (Bichel and Hansen, 1972).

ii) Uptake in animal tumours has been shown to be reduced by prior whole-body irradiation. This seems to be due to transferrin being saturated with iron, and is partially countered by the addition of transferrin (Bradley, Alderson, Eckelman, 1978).

iii) Hammersley and Zivarovic (1976) studied cultures of HeLa cells and noted that gallium uptake was lowest during the most rapid DNA synthesis but maximum uptake occurred during the protein synthesis phase of the cell cycle.

iv) Sephton and Harris (1974, 1977) have shown that transferrin stimulates gallium uptake of tumour cells in vitro.

v) Hayes (1976) showed that when scandium is simultaneously administered with gallium citrate the gallium clears rapidly from soft tissues. Since uptake into tumours is not effected, the ratio of tumour uptake/
non-tumour uptake increases. Unfortunately, scandium causes severe haemolytic anaemia in humans.

vi) Stable gallium nitrate has been shown to have some anti-tumour properties in rodents, and might be active against solid tumours in humans (Hart, Smith, Yancy, 1971).

The following hypothesis of the mechanism of gallium-67 localization in tumours has been put forward by Larson (1978):

After gallium-citrate is injected intravenously it rapidly binds to transferrin to form gallium transferrin. This becomes distributed throughout the transferrin pool, but only a fraction of the gallium transferrin interacts with a specific transferrin receptor on the tumour cell. The gallium transferrin, after binding to the cell, is taken intact into the tumour cell. Thus, the gallium transferrin is the active radiopharmaceutical in vivo.

Within the cell the gallium is deposited in lysosomes before subcellular distribution. Some gallium is stored along with iron in ferritin, but more is carried to microvesicles and rough endoplasmic reticulum. Here it binds to other macromolecules, and the ultimate fate of the gallium depends on the individual cell biology.

This process is shown schematically in Figure 13-1.
Figure 13-1 Proposed mechanism of gallium localization (Larson 1978)
CHAPTER 14

SCINTILLATION DETECTORS

Section 14-1: Principles of the Gamma Scintillation Counter

Because of their high density solid detectors have higher counting efficiencies than ion collection detectors, e.g. the Geiger-Müller tube, which use gas as the medium in which ion pairs are formed by incident radiation. A class of solids called fluors, or scintillators, is very suitable for this role. They have the property of fluorescence which is the emission of visible or ultra-violet light when ionizing radiation is incident on them. This effect is due to atoms being excited when a particle or photon passes through the scintillator; photons are then emitted in the de-excitation process.

Different scintillators are suitable for detecting different types of radiation. Zinc sulphide is used to detect heavy particles such as protons or α-particles. In fact, the first scintillation counter was built in 1903 by Sir William Crookes, and consisted of a ZnS screen with a microscope to observe the flashes of light when α-particles hit the screen. Crystals of anthracene, or napthalene containing a small amount of anthracene, have been used for the detection of β-particles.
However, plastic scintillators e.g. polystyrene with terphenyl added, are now the materials of choice. They have the advantages of being cheap and that they can be bought in large sheets and can be machined to any desired shape.

Sodium iodide is suitable for X- and γ-ray detection because its high density and the high atomic number of iodine (Z = 53) make it an effective absorber of low and medium energy photons. Pure sodium iodide does not scintillate at room temperature so it is usually doped with thallium to act as an activator. The thallium atoms form luminescence centres which can be excited even at room temperature. Sodium iodide is hygroscopic and therefore must be hermetically sealed to prevent yellow discoloration.

Some of the physical properties of these scintillators are listed below. Note that the emission of photons after being excited by ionizing radiation is exponential, and the decay time is defined as being the time interval necessary for 67% of photons to be emitted.

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density (g/cm³)</th>
<th>Maximum wavelength emitted (nm)</th>
<th>Decay Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na I</td>
<td>3.67</td>
<td>410</td>
<td>$0.25 \times 10^{-6}$</td>
</tr>
<tr>
<td>Stilbene</td>
<td>1.19</td>
<td>410</td>
<td>$8 \times 10^{-9}$</td>
</tr>
<tr>
<td>ZnS (Ag)</td>
<td>4.10</td>
<td>450</td>
<td>$9 \times 10^{-9}$</td>
</tr>
<tr>
<td>p-Terphenyl</td>
<td>1.17</td>
<td>410</td>
<td>$10 \times 10^{-9}$</td>
</tr>
<tr>
<td>Anthracene</td>
<td>1.24</td>
<td>440</td>
<td>$26 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
There are three interactions by which photons are absorbed in the Na I (Tl) crystal, viz:

i) Pair production: the formation of an electron-positron pair in the field of a nucleus. This predominates if $E_\gamma >> 1$ Me V

ii) Compton scattering: the elastic scattering of a photon by a free charged particle (usually an electron)

iii) Photoelectric effect: the photon gives up all of its energy to a bound electron and removes it from the atom. This is strongly energy dependent and predominates for $E_\gamma << 1$ Me V.

Whichever absorption process is involved, high energy secondary photons are produced. These lose their energy by ionization, and this energy results in secondary photons, or luminescent quanta, being emitted as electrons replace those removed from the ionized atoms. Usually twenty to thirty secondary photons are emitted per keV of energy loss (Rollo, 1977).

In order to improve the counting statistics photomultiplier (PM) tubes are connected to the Na I (Tl) crystal by light pipes. A schematic of a PM tube is shown in Figure 14-1. It contains a photocathode and
a series of typically ten to fourteen cesium-antimony dynodes. By means of a stable high-voltage supply (~1 kV) and a voltage divider each dynode is maintained at a successively higher potential. The inside of the tube is coated with highly reflective magnesium oxide to minimise light losses.

Secondary photons emitted by the Na I (Tl) crystal pass through the light pipe to strike the photocathode. Electrons are ejected from the surface of the photocathode by the photoelectric effect. One electron is released for each seven to ten photons incident on the photocathode. The freed electrons are accelerated to the first dynode where each electron frees four to eight secondary electrons by giving up their kinetic energy. The shape of the dynodes is such that the electrons are accelerated to the next dynode (of higher potential), where more secondary electrons are released. This multiplication effect takes place at each of the dynodes, giving an overall gain of $10^6$ to $10^7$ electrons for each electron released at the photocathode.

The pulse of electrons at the final dynode produces a negative output pulse, the height of which is proportional to the energy originally absorbed by the Na I (Tl) crystal. This output pulse is fed into a preamplifier to change the pulse shape and an amplifier increases the pulse height to an amplitude sufficient for use in an energy discriminator, or pulse-height analyzer (PHA).
Figure 14-1 Details of photomultiplier tube
The PHA is an electronic circuit that accepts the pulses from a radiation detector, like that described above, and only counts those which fall in a selected range. Since pulse height is directly proportional to the energy of the photon absorbed by the detector it only counts pulses caused by radiation in a certain energy range. The lower limit of this is known as the baseline $E$, and the upper limit is $E + \Delta E$, where $\Delta E$ is known as the window width or energy window. Pulses that are accepted are passed to a scaler and possibly a rate-meter.

The counting system described above constitutes a single-channel analyzer (SCA). This may be used to measure the (differential) spectrum of a radio-isotope by setting the energy window to a narrow range. Counts are then recorded for each baseline setting as it is increased in increments equal to the energy window. A graph of counts versus baseline setting would give the spectrum. This, of course, is not a practical approach. Setting up the hundred or more baseline levels is an extremely tedious and difficult task. It would also be time-consuming and not suitable for use with short-lived radio-isotopes.

It is apparent that pulse-height analysis system with many channels, i.e. a multi-channel analyzer (MCA), is required. One of the first MCA's used multiple discriminators with levels set $\Delta E$ apart (Figure 14-2).
Pulses falling between bias levels B₀ and B₁ will be counted in channel 1, pulses falling between bias levels B₁ and B₂ will be counted in channel 2, and so on. The plot on the right of Figure 14-2 shows how many pulses of each amplitude occurred.

Generally at least a hundred channels are needed and each requires its own scaler, and this resulted in large pieces of hardware. Multiple scalers were substituted by ferrite-core store (memory) in the mid-1950's. These memories have reasonably fast read/write times and are small, reliable and continually getting cheaper.

However, accurately setting up and maintaining a large number of discriminator bias levels is extremely difficult, and so a different approach is now used. Advantage is taken of the fact that while it is difficult to directly divide the input pulse quickly and directly into small discrete levels, it is relatively easy to divide time into small amounts. Hence, the input pulse is treated in the following manner:

The pulse is "stretched" (Figure 14-3) to maintain the voltage at its maximum level. Then at time $t₀$ the stretched pulse voltage is removed linearly until it reaches zero at time $t$. Time $t$ is therefore proportional to pulse height and also therefore to the energy absorbed by the detector. An oscillator produces clock pulses at a predefined rate and from Figure 14-3 it is
Figure 14-2: Multi-discriminator analyzer
apparent that the interval between pulses is analogous to the channel widths of a multidiscriminator analyzer. Thus the number of clock pulses between \( t_0 \) and \( t \) can be used to determine the appropriate channel. This system is more linear than the multidiscriminator method because the time interval between clock pulses and the run-down slope can be kept very constant.

Amplifiers produce a large number of low amplitude noise pulses. Since these can be treated as normal input, a single pulse discriminator (ULD) is used. This prevents false pulses reaching the "stretcher". Similarly, an upper-level discriminator (ULD) is used to prevent pulses in the range that are not of interest being processed. The ULDs are thereby provide more time for the NCA to handle data of interest, and prevent distortion of a spectrum by undesirable data.

Figure 14-3 is a schematic diagram of an NCA.

Figure 14-3: Pulse stretching

Section 14-2: Gamma-Ray Spectra

Consider a radio-isotope that emits photons that are essentially monoenergetic. One might expect that the spectrum measured by a scintillation detector would look like that in Figure 14-3a. It would, however, look like that in Figure 14-3b. The broadening of the photopeak is standardized in energy. When the incident \( \gamma \)-ray of energy \( E \) is absorbed by the Na I (TI) crystal
apparent that the interval between pulses is analogous to the channel widths of a multidiscriminator analyzer. Thus the number of clock pulses between $t_0$ and $t$ can be used to determine the appropriate channel. This system is more linear than the multidiscriminator method because the time interval between clock pulses and the run-down slope can be kept very constant.

Amplifiers produce a large number of low amplitude noise pulses. In order that these are not treated as normal input pulses a lower-level discriminator (LLD) is used. This prevents such pulses reaching the "stretcher". Similarly, an upper-level discriminator (ULD) is used to prevent pulses which are too large to be of interest being processed. the LLD and ULD thereby provide more time for the MCA to handle data of interest, and prevent distortion of a spectrum by undesirable data.

Figure 14-4 is a schematic diagram of an MCA.

Section 14-2: Gamma-ray Spectra

Consider a radio-isotope that emits photons that are essentially monoenergetic. One might expect that the spectrum measured by a scintillation detector would look like that in Figure 14-5a. It would, however, look like that in Figure 14-5b. The broadening of the photopeak is statistical in nature. When the incident $\gamma$-ray of energy $E_{\gamma}$ is absorbed by the Na I (Tl) crystal
input pulses
amplifier

Linear gate

Stretcher

Discriminator

Run-down

Oscillator

Gate

Scaler

Channel number to storage device.

FIGURE 14-4 Schematic of MCA
a photoelectron with energy $E_0 = E_2$ is produced. The
photoelectron then produces $n e^+$ light quanta, each with
energy of about 2 eV (corresponding to $E_0 / 400$ ev),
by ionizing all the atoms in the crystal. If $n_e^+$ is
the efficiency of conversion of excitation energy into
light quanta, then
\[ n_e^+ = \frac{E_2}{E_1} \]
Now, only a fraction $v$ of the $n_e^+$ light quanta
will be collected by the photomultiplier, and each
hitting the photocathode has a probability of $\alpha$ of
ejecting an electron. Therefore, the number of electrons
produced at the input of the photomultiplier is
\[ n_0 = n_e^+ v \alpha \]

All of the processes involved are very complicated
and hence $n_0$ will be subject to random fluctuations.
If $n$ is the average number of electrons produced at
the photocathode, then the probability $P(n)$ of there
being $n$ electrons is given by the Poisson distribution.

FIGURE 14-5: (a) Theoretical and (b) measured
spectrum of nuclide with monoenergetic
decay
a photoelectron with energy $E_e = E_{\gamma}$ is produced. The photoelectron then produces $n_{q1}$ light quanta, each with energy of about 3 eV (corresponding to $\lambda = 400$ nm), by ionization of atoms in the crystal. If $\varepsilon_{\text{light}}$ is the efficiency of conversion of excitation energy into light quanta then

$$n_{q1} = \frac{E_{\gamma}}{E_{1q}} \varepsilon_{\text{light}} \quad (14.1)$$

Now, only a fraction $\varepsilon_{\text{coll}}$ of the $n_{q1}$ light quanta will be collected by the photocathode, and each electron hitting the photocathode has a probability of $\varepsilon_{\text{cathode}}$ of ejecting an electron. Therefore, the number of electrons produced at the input of the photomultiplier is

$$n_e = \frac{E_{\gamma}}{E_{1q}} \varepsilon_{\text{light}} \varepsilon_{\text{coll}} \varepsilon_{\text{cathode}} \quad (14.2)$$

Typical values of these efficiencies are (Frauenfelder and Henley, 1974):

$$\varepsilon_{\text{light}} = 0.1 \quad \varepsilon_{\text{coll}} = 0.4 \quad \varepsilon_{\text{cathode}} = 0.2$$

All of the processes involved in (14.2) are statistical and hence $n_e$ will be subject to random fluctuations. If $\bar{n}$ is the average number of electrons produced at the photocathode, then the probability $P(n)$ of there being $n$ electrons is given by the Poisson distribution:
For large \( n \), \( n \) can be considered to be a continuous variable and the distribution is then approximated by the normal distribution:

\[
P(n) = \frac{(\bar{n})^n}{n!} e^{-\bar{n}}
\]

(14.3)

The standard deviation of this distribution is given by:

\[
\sigma = \sqrt{n}
\]

(14.5)

while \( \Delta n \), the full-width at half-maximum (FWHM) is

\[
\Delta n = 2.35 \sigma
\]

(14.6)

The fractional energy resolution is defined as the ratio of the FWHM of the photopeak to the energy of the incident photon, i.e. \( \Delta E / E \gamma \), and is also equal to \( \Delta n / \bar{n} \).

Most of the counts observed at energies below the photopeak are due to Compton-scattered photons; scattering may occur in either the source or the crystal.

If \( E \) is the energy (in MeV) of the primary photon which scatters an electron at an angle \( \theta \) to the direction of the primary photon then the kinetic energy of the scattered electron is

\[
T \quad (\text{MeV}) = \frac{E^2 (1 - \cos \theta)}{0.511 + E(1 - \cos \theta)}
\]

(14.7)
Compton electrons acquire energy ranging continuously from zero to a maximum value at $\theta = 180^\circ$ of

$$T_{\text{max}} = \frac{E^2}{0.255 + E} \quad (14.8)$$

If an electron is scattered in the detector crystal and the scattered photon leaves the crystal then the energy absorbed in the crystal will be just that of the Compton electron. The detector then shows a response from zero to $T_{\text{max}}$ and the upper level of this continuum is known as the Compton edge. Although this has a discrete value, it is statistically broadened as described above.

Another feature of the spectrum is the backscatter peak, which is the result of photons being Compton scattered by $180^\circ$ relative to the original photon before reaching the crystal. The energy of the backscatter peak is given by

$$E_{\text{bs}} = E_{\gamma} - T_{\text{max}} \quad (14.9)$$

Figure 14.5b shows the Compton edge and backscatter peak.

Sodium iodide crystals are usually encased in lead to reduce background or have collimators to limit the field-of-view of the detector. Lead has a high atomic number ($Z = 82$) and incident photons will be absorbed mainly by the photoelectric effect. As electrons return
to the K-shell the characteristic K X-rays of lead are emitted and may be absorbed by the Na I (Tl) crystal. This results in a peak occurring at 77 keV (Figure 14.6).

Also, photons incident on the crystal often undergo the photoelectric process. This usually occurs in the iodine atoms because it has higher atomic number than sodium, and results in 28 keV K X-ray of iodine being emitted. If the original photon was absorbed near to the crystal surface, which is more common for lower energy photons, the K X-ray may escape the crystal. The nett energy absorbed is therefore equal to the energy of the incident photon minus 28 keV. The resulting photopeak is known as an iodine escape peak.
 CHAPTER 15

PRINCIPLES OF THE GAMMA CAMERA

The gamma camera is a device for visualizing the distribution of radioactively labeled compounds within the human body as a diagnostic technique. Among the first gamma cameras was the Anger camera, after its inventor, Dr. Philip Anger. It has been available commercially since the mid-1960s, and its performance has improved significantly since then. It has now replaced the parallel-hole scanner as the instrument of choice for imaging procedures.

A gamma camera consists of two major parts, the head which detects gamma-rays and generates electrical signals corresponding to the information and the console which processes the signals to form an image. The head is composed of a collimator and a scintillation crystal with an array of photomultiplier tubes connected to it by a transparent light pipe. These components are shown schematically in Figure 15-1.

Section 15-1. Collimators

The collimator focuses the radiation from the active source such that it is directed at the detector to form a two-dimensional image of its distribution. A collimator consists of a plate of dense material, usually lead but sometimes tungsten,
CHAPTER 15

PRINCIPLES OF THE GAMMA CAMERA

The gamma camera is a device for visualizing the distribution of radioactive compounds in the human body as a diagnostic technique. Also known as the Anger camera, after its inventor H.O. Anger, it has been available commercially since the mid-1960's and its performance has been steadily improved since then. It has now replaced the rectilinear scanner as the instrument of choice for imaging procedures.

A gamma camera consists of two major parts, the head which detects the γ-rays and generates electrical signals corresponding to the position of absorption and the console which processes the signals to form an image. The head is composed of a collimator and a scintillation crystal with an array of photomultiplier tubes connected to it by a transparent light pipe. These components are shown schematically in Figure 15-1.

Section 15-1: Collimators

Gamma-rays are emitted isotropically by a radioactive source and it is therefore necessary to collimate the radiation in order to form a two-dimensional image of its distribution. A collimator consists of a plate of dense material, usually lead but sometimes tungsten,
with an array of holes arranged such that only photons travelling in a certain direction can reach the crystal. There are four collimator types viz. parallel-hole, pinhole, converging and diverging collimators.

A parallel-hole collimator is shown in Figure 15-2. The geometric spatial resolution can be expressed in terms of the radius of the collimator holes \( r \), the distance from the collimator to the source \( b \) and the distance from the upper collimator face to the crystal \( c \) as (Rollo, 1977):

\[
R_{gp} = \frac{2r(t_e + b + c)}{t_e}
\]  

(15-1)

t_e is the effective collimator length given by \( t_e = t - \frac{2}{u} \) because of photon penetration of the material between the holes (i.e. the septa) at both ends of the collimator. Here \( u \) is the mean free path of photons of a given energy in the collimator material.

From equation (15-1) it is apparent that geometric spatial resolution can be improved by decreasing the radius of the holes or by using a thicker collimator i.e. increasing \( t \). Manufacturers usually produce a range of high-resolution all-purpose and high-sensitivity collimators for use with a given energy range.

Another parameter of a collimator is the geometric efficiency which is the fraction of photons emitted by a planar source which are detected. If 'a' is the area of the \( N \) collimator holes then the geometric
Signals sent to console

Electronic processing and transmission line drivers

Preamplifiers

Photomultiplier tubes

Light pipe

Crystal

Collimator

Figure 15-1 Gamma camera head layout

Figure 15-2 Parallel hole collimator
efficiency is

\[ G_p = \frac{Na}{4\pi t e^2} \]  

(15-2)

Note that it is independent of the distance from the collimator to the source, and it would therefore be expected that a given planar source (larger than the field-of-view of the camera) would produce a constant count rate at all distances from the collimator. Moyer (1974) showed that there is in fact a slight decrease in count rate with distance (Figure 15-5).

Parallel-hole collimators are the most common collimator in clinical use. However, pinhole collimators (Figure 15-3) are used when their magnifying properties are needed e.g. when imaging the thyroid gland. The geometric spatial resolution is given by

\[ R_{\text{ph}} = \frac{(t+b)d_e}{t} \]  

(15-3)

where \( d_e \) is the effective diameter of the pinhole aperture and is defined as

\[ d_e = \left[d(d+2u^{-1}\tan \alpha)\right]^{1/2} \]  

(15-4)

For a point source located at an angle \( \theta \) from the collimator axis the geometric efficiency of a pinhole collimator is
In the special case of the source being on the axis ($\theta = 0$) the geometric efficiency becomes

$$G_{ph} = \frac{d^2 e}{16 b^2}$$

(15-6)

The effect of the distance from source to the collimator ($b$) on resolution and efficiency is shown in Figures 15-5 and 15-6 respectively.

Converging collimators (Figure 15-4) have a series of holes which converge to a point a distance $f$ below the collimator. It has similar magnifying properties to the pinhole collimator, but magnification is not constant with distance from the collimator. Burdine and Murphy (1975) report that images formed with converging collimator are distorted when they involve thick organs. This is because structures further from the collimator tend to appear larger than those closer to it.

The spatial resolution in the object plane of a converging collimator is given by (Moyer, 1974):

$$R_{ge} = \frac{t + b + c}{t_e} \left[ \frac{1}{\cos \theta} \right] \left[ 1 - \frac{c + \frac{1}{2}t_e}{f + t_e + c} \right]$$

(15-7)

where $t_e = \frac{t - 2u^{-1}}{\cos \theta}$

(15-8)

is the effective collimator length at angle $\theta$ from the collimator axis.
Figure 15-3  Pinhole collimator

Figure 15-4  Converging collimator
Figure 15-5  Effect of distance on resolution with
(A) high sensitivity (B) diverging
(C) all-purpose (D) converging (E) high
resolution and (F) pinhole collimators
(from Moyer 1974)

Figure 15-6  Effect of distance on efficiency with various
collimators (as above)  (from Moyer 1974)
The geometric efficiency is given by

\[ G_c = \frac{Nf^2}{(f-b)^2} \frac{\pi r^2}{4\pi t^2} \]  

(15-9)

Note that the efficiency increases with distance from the collimator, in contrast to the parallel-hole and pinhole collimators.

Diverging collimators were designed to increase the field of view of cameras with small crystals (10 inch). It was used for imaging larger organs e.g. liver or lungs. Unfortunately both spatial resolution and geometric efficiency degrade with distance from the source to the collimator. Newer cameras with large fields of view (~15 inch) mean that diverging collimators are not commonly used now.

Section 15-2: Detector Crystal and Head Circuitry

The photons that are allowed to pass through the collimator are then absorbed by a NaI(Tl) crystal as described in the previous chapter. Most gamma cameras employ ½ inch thick crystals and the detection efficiency as a function of energy is shown in Figure 15-7. A thicker crystal would increase this efficiency but the accuracy with which a scintillation event can be localized depends on minimizing multiple Compton interactions. A thickness of ½ inch provides the best compromise between these two requirements.

Originally gamma cameras had an array of nineteen
2-inch PM tubes but large field of view cameras now commonly have thirty-seven 3-inch tubes. The tubes are arranged in a hexagonal array as shown in Figure 15-8.

The light from a scintillation event produces an output current pulse from each of the PM tubes. However, the nearer a tube is to an event the more light it will receive and hence the larger will be its output pulse and this can be used to determine the position of the event. The output pulses pass through a preamplifier to shape and amplify them before being input to a resistor matrix. This matrix is shown schematically in Figure 15-8, and combines all of the outputs from the preamplifiers into the four position signals $X^+$, $X^-$, $Y^+$ and $Y^-$. Summing amplifiers then act as line drivers and amplify the signals for the transmission via cable to the camera console.

Section 15-3: Console Circuitry

Higher energy photons will produce larger signals and so the four positioning signals are attenuated to give all signals the same range of amplitude. This is controlled by an "energy range" switch such that at higher energy isotope settings the signals are attenuated more.

Each of the four outputs from the attenuators then follows two different paths. In one path all of the signals are summed to form the "Z-pulse" which has an amplitude proportional to the energy of the photon absorbed by the crystal. The Z-pulse is fed into a pulse-
Figure 15-7 Efficiency of $\frac{1}{2}$" gamma camera crystal

\[
x = \frac{1}{2} (x' - (x'))
\]
\[
y = \frac{1}{2} (y' - (y'))
\]

Figure 15-8 Gamma camera head resistor matrix
height analyzer (PHA) and if it is outside the range determined by the "energy range" and "window width" switches on the console then that pulse is ignored and nothing further happens. However, if the pulse is within the window an analyzer output pulse is sent to the control signal generator which in turn enables the line amplifiers and stretchers (see Figure 15-9).

Now, the other path that the attenuator output signals follow is through delay lines. These delay the signals by 1.2 us which is the time required for the PHA and control signal generator to operate. The signals are then stretched from being 1 us wide to 3.5 us and thence are fed into differential amplifiers. The X- and Y- positions of the scintillation event are calculated as

\[
X = \frac{K}{Z} [(X^+) - (X^-)] \quad (15-10)
\]

\[
Y = \frac{K}{Z} [(Y^+) - (Y^-)] \quad (15-11)
\]

where \(X^+, X^-, Y^+, Y^-\) are the amplitudes of the signal pulses, \(Z\) is the amplitude of the Z-pulse and \(K\) is a constant. The factor \(K/Z\) is the amplifier gain, and removes the energy dependence from the positioning signals.

The X- and Y- signals are then sent to X- and Y- deflection drivers which position a spot on a cathode-ray tube (CRT) and the blanking is switched off by the control signal generator. This results in a spot being illuminated on the CRT in a position corresponding to
the original scintillation event. A block diagram of this circuitry is shown in Figure 15-9.

It is becoming more common for the position signals to be digitized by analogue-to-digital converters (ADC's) so that the information can be stored by a computer. This will not be covered in detail here.
Figure 15-9 Block diagram of gamma camera
CHAPTER 16

OPTIMIZATION OF GALLIUM-67 IMAGES

Section 16-1: Aim

Gallium-67 imaging has been employed for about ten years for the detection of neoplastic and inflammatory lesions and much clinical literature is now available on this subject. However, the technical factors adopted in different centres are fairly diverse and the reasons for their selection are rarely discussed in detail.

The present research was conducted to consider the physical principles of forming images of Ga-67 distribution in the body, and thereby determine the optimum conditions for the formation of these images. Ideally the operation of a gamma camera should be organized towards the best combination of spatial resolution and sensitivity. Obviously, the better the resolution of the imaging system the greater the accuracy with which anatomical sites can be localized. The sensitivity of the system reflects the efficiency with which it detects radiation and high sensitivity is desirable for two reasons. Firstly, it allows the radiation dose to the patient to be minimized and secondly it reduces the level of statistical noise, or quantum mottle, in the images. Note, however, that it is only desired to detect primary radiation and to reject secondary, or scattered, radiation.
Gallium-67 decays by electron capture with a 78 hour half-life. Its decay scheme is shown in Figure 16-1 (Dillman and Van der Lage, 1975) and Table 16-1 lists the relative abundancies of its main $\gamma$-emissions.

**Table 16-1 Isomeric Transitions of Ga-67**

<table>
<thead>
<tr>
<th>$E$(keV)</th>
<th>Relative Abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>42 *</td>
</tr>
<tr>
<td>184</td>
<td>24</td>
</tr>
<tr>
<td>206</td>
<td>2.5</td>
</tr>
<tr>
<td>296</td>
<td>22</td>
</tr>
<tr>
<td>388</td>
<td>7</td>
</tr>
<tr>
<td>others</td>
<td>weak</td>
</tr>
</tbody>
</table>

*29% of the 92 keV photons undergo internal conversion*

The number and range of energy of the photopeaks places unusual constraints on the choice of collimator and of analyzer window(s), and this is responsible for the lack of a standard set of operational parameters. This is in contrast to imaging with the more commonly used radionuclide technetium $-99m$ which has a single photopeak at 140 keV.

In the present research the most suitable operational parameters were determined by experimentally seeking answers to the following questions:

a) What collimator design is optimum?

b) How many Ga-67 photopeaks should be included?

c) What analyzer settings (windows) are necessary to
**Figure 16-1 Ga-67 Decay scheme (from Dillman and Van der Lage 1975)**

<table>
<thead>
<tr>
<th>Transition</th>
<th>Mean Energy (MeV)</th>
<th>Decay Mode</th>
<th>Half Life (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Capture</td>
<td>0.559</td>
<td>111.1</td>
<td>78.5 hours</td>
</tr>
<tr>
<td>Electron Capture</td>
<td>0.370</td>
<td>111.1</td>
<td>78.5 hours</td>
</tr>
<tr>
<td>Electron Capture</td>
<td>0.370</td>
<td>111.1</td>
<td>78.5 hours</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.2290</td>
<td>111.1</td>
<td>78.5 hours</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.2290</td>
<td>111.1</td>
<td>78.5 hours</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.2290</td>
<td>111.1</td>
<td>78.5 hours</td>
</tr>
</tbody>
</table>

**Graph**

**Electron Capture Decay**

![Ga-67 Decay Scheme](image)
maximise sensitivity whilst keeping Compton scattered radiation to a minimum?

Section 16-2: The Gallium-67 Spectrum

Section 16-2-1: Method

Differential energy spectra from Ga-67 were generated by analyzing the Z-signal from a gamma-camera with a multi-channel analyzer (MCA). The spectra were measured with a range of collimators viz. high, medium and low energy collimators. A distributed source was used which consisted of Ga-67 in 50 ml saline, sealed in a plastic centrifuge tube. To reduce the amount of radiation scattered from the surroundings the source was supported 50 cm above the floor by a retort stand, with the face of the collimator 30 cm from the source.

Spectra were also measured with the source at the bottom and near the top of a plastic bucket, containing 10 cm depth of water. This was done to simulate the scatter conditions occurring in vivo. All spectra were corrected for background counts.

Section 16-2-2: Apparatus

The gamma camera available was a Toshiba model GCA-202 camera. This is a large field-of-view camera (35 cm) and a photograph of it in clinical use is shown in Figure 16-2.
Table 16-1 lists some of the physical properties of the three collimators used. The number of holes and the maximum energy photons usable with each collimator are

FIGURE 16-2: GCA-202 gamma camera taking a scan

The MCA used to generate the spectra was a 256-channel Nuclear Data model. This was calibrated by the method below to 1.6 keV/channel, giving a usable energy range of 0 to 184 keV.

Use was made of the 121 keV and 196 keV photopeaks of Ga-67. With the desired calibration there would be 136 channels (e.g., 2.6 keV = 2.6 keV/11.5 keV/channel) between these peaks on the MCA. The "energy range" switch on the gamma-camera determines the attenuation of the 2-pulse

Table 16-2 lists some of the physical properties of the three collimators used. The number of holes and the maximum energy photon usable with each collimator are as given in the manufacturers specifications, but the cross-sectional area of each hole was measured experimentally. This was achieved by placing a sheet of 24 cm x 30 cm film against the face of each collimator and X-raying it. The size of the holes can then be directly measured from the developed film and the area calculated.

Table 16-2 Physical Properties of Collimators

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Material</th>
<th>No. of holes</th>
<th>Cross-sectional Area of each hole (mm²)</th>
<th>Maximum Usable Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>low energy</td>
<td>lead</td>
<td>42,000</td>
<td>2.3</td>
<td>150</td>
</tr>
<tr>
<td>medium energy</td>
<td>tungsten</td>
<td>8,000</td>
<td>9.1</td>
<td>250</td>
</tr>
<tr>
<td>high energy</td>
<td>lead</td>
<td>1,800</td>
<td>33.2</td>
<td>410</td>
</tr>
</tbody>
</table>

The MCA used to generate the spectra was a 256-channel Nuclear Data model. This was calibrated by the method below to 1.5 keV/channel, giving a usable energy range of 0 to 384 keV.

Use was made of the 92 keV and 296 keV photopeaks of Ga-67. With the desired calibration there would be 136 channels \(=(296 \text{ keV}-92 \text{ keV}) : 1.5 \text{ keV/channel}\) between these peaks on the MCA. The "energy range" switch on the gamma-camera determines the attenuation of the Z-pulses.
(see Section 15-3), and so this was adjusted to give the desired separation between the photopeaks. The "fine zero" of the MCA was then adjusted so that the 292keV photopeak coincides with MCA channel 192 (=292keV / 1.5 keV / channel). The settings used for the measurements of spectra were:

Gamma Camera: Energy range 220 keV Coarse
               2.80   Fine

Multi-channel analyzer: LLD = 0.20
                       ULD  = 10.00
            conversion gain = 512
              group    = 256
             fine zero = 0.0
zero suppression= all
   DC/AC     = AC
           strobe  = off
          mode    = normal

Hard copies of spectra were obtained by connecting the MCA to a Rikadenki chart recorder model BW-201.

Section 16-2-3: Results

All of the spectra measured under "scatter-free" conditions were collected for 400 seconds, with a Ga-67 source of activity approximately 0.5 mCi. Figures 16-3, 16-4 and 16-5 show the spectra when high, medium and low energy collimators respectively were used. The total counts in each spectrum are given in Table 16-3.
FIGURE 16-3: Ga-67 - scatter-free, high energy collimator
FIGURE 16-4: Ga-67 - scatter-free, medium energy collimator
The spectra taken under simulated in vivo conditions and absorption in tissues were also collected for comparison, with a source of activity approximately 0.3 millicuries. The spectra obtained with the three collimators under study are shown in Figures 16-6 to 16-10. (Note the different ordinate scales in these figures.) Table 16-4 lists the total counts per spectrum.

![Graph](image-url)

**FIGURE 16-5:** Ga-67 - scatter-free, low energy collimator
Table 16-3 Total Counts in Spectrum

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>high energy</td>
<td>960,382</td>
</tr>
<tr>
<td>medium energy</td>
<td>1,136,768</td>
</tr>
<tr>
<td>low energy</td>
<td>5,397,348</td>
</tr>
</tbody>
</table>

The spectra taken under simulated in vivo scatter and absorption conditions were also collected for 400 seconds, with a source of activity approximately 0.1 mCi. The six spectra obtained with the three collimators under two scattering conditions are shown in Figures 16-6 to 16-11. (Note the different ordinate scales in these figures.) Table 16-4 lists the total counts per spectrum.

Table 16-4 Total Counts in Spectrum

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Depth under Water (cm)</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>high energy</td>
<td>10</td>
<td>224,239</td>
</tr>
<tr>
<td>high energy</td>
<td>0</td>
<td>409,321</td>
</tr>
<tr>
<td>medium energy</td>
<td>10</td>
<td>301,604</td>
</tr>
<tr>
<td>medium energy</td>
<td>0</td>
<td>569,870</td>
</tr>
<tr>
<td>low energy</td>
<td>10</td>
<td>1,434,716</td>
</tr>
<tr>
<td>low energy</td>
<td>0</td>
<td>4,139,379</td>
</tr>
</tbody>
</table>
FIGURE 16-6  Ga-67 - with absorption and scatter, high energy collimator
FIGURE 16-7: Ga-67 - with scatter, high energy collimator
FIGURE 16-8  Ga-67 - with scatter and absorption, medium energy collimator
FIGURE 16-9  Ga-67 – with scatter, medium energy collimator
FIGURE 16-10  Ga-67 - with scatter and absorption, low energy collimator
Examination of Figure 16-1 reveals that the most notable features of the scatter-free spectrum with the high-energy collimator are the low level of scatter radiation, and the characteristic absorptions due to impurities imposed on the spectrum of 59 keV. The relative heights of the photopeaks are not as high as would be expected from Table 16-1, but this can be explained by the variation with energy of the intrinsic efficiency of the thick NaI(Tl) crystal. Intrinsic efficiency is defined by

$$
\text{Efficiency} = \frac{1 - e^{-\mu x}}{\mu x}
$$

where $\mu$ is the absorption coefficient. Using values for $\mu$ given by Cross (1960), the intrinsic efficiency of the crystal at each of the photopeaks is calculated and the results summarized in Table 16-2.

**FIGURE 16-11** Ga-67 - with scatter, low energy collimator
Section 16-2-4: Discussion

Examination of Figure 16-3 reveals that the most notable features of the scatter-free spectrum with the high-energy collimator are the low level of scattered radiation, and the characteristic X-rays of lead superimposed on the spectrum at 75 keV. The two higher energy photopeaks are not as high as would be expected from Table 16-1, but this can be explained by the variation with energy of the intrinsic efficiency of the 12 mm thick NaI(Tl) crystal. Intrinsic efficiency $\xi$ is defined by

$$\xi(E) = 1 - e^{-\mu(E)x}$$  \hspace{1cm} (16-1)

where $\mu(E)$ is the absorption coefficient. Using values for $\mu(E)$ given by Crouthamel (1960), the intrinsic efficiency of the crystal at each of the photopeaks was calculated and the results summarised in Table 16-5.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>$\mu$ (cm$^{-1}$)</th>
<th>$\xi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>5.790</td>
<td>100</td>
</tr>
<tr>
<td>184</td>
<td>1.4135</td>
<td>82</td>
</tr>
<tr>
<td>296</td>
<td>0.572</td>
<td>50</td>
</tr>
</tbody>
</table>

The spectrum obtained with the medium-energy collimator (Figure 16-4) has a similar profile to that with the high
energy collimator. There are, however, some important differences. The relative height of the 92 keV photopeak has decreased, while that of the 296 keV photopeak has increased. There is also more scattered radiation. The characteristic X-rays of tungsten are clearly evident at 59 keV.

Figure 16-5 shows the Ga-67 spectrum obtained with a low energy collimator to differ dramatically from the other two spectra. There is greater transmission of radiation throughout the energy range, and, as is to be expected, this is most pronounced at higher energies. The amount of Compton-scattered radiation is much greater than in the other spectra. In particular, the Compton peak of the 296 keV transition is distinct at 159 keV. As with the high energy collimator the characteristic X-rays of lead are present.

Spectra with the source at the top of a bucket of water (i.e. backscatter conditions) show a general increase in the amount of scattered radiation. There are, however, no backscatter peaks evident (see Section 12-2 and Table 16-6).

Table 16-6 Backscatter Peaks of Ga-67

<table>
<thead>
<tr>
<th>Photopeak Energy (keV)</th>
<th>Backscatter Peak Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>68</td>
</tr>
<tr>
<td>184</td>
<td>107</td>
</tr>
<tr>
<td>296</td>
<td>137</td>
</tr>
</tbody>
</table>
In the spectra measured with lead collimators (Figures 16-7 and 16-11) the peaks due to the 75 keV lead X-rays are more distinct from the 92 keV photopeak than in the spectra taken under scatter-free conditions.

When the source is placed under 10 cm of water (i.e. absorption plus scattering conditions) the spectra changed somewhat. The photopeaks are differentially attenuated, with the 92 keV peak being much more reduced in height than the higher energy peaks. The level of scattered radiation has increased to such an extent that in spectra with a lead collimator in use the 92 keV peak is indistinguishable from the 75 keV lead X-rays. The spectra are not as "clean" as the others i.e. there is more statistical noise due to the decreased count rate.

Consideration of Figures 16-5, 16-10 and 16-11 shows that a low energy collimator is not suitable for use in Ga-67 imaging as the thin septa allow too much higher energy radiation to be transmitted. Even if imaging was to be done using only radiation from the 92 keV peak, use of a low energy collimator would mean that a significant proportion of photons in that region would be due to higher energy photons that had been Compton-scattered. This would unacceptably degrade resolution. The choice between the medium and high energy collimators can be made after measurements of sensitivity and resolution.
Section 16-3: Sensitivity and Resolution

Section 16-3-1: Method

For resolution measurements a "point" source was required. This consisted of a 19-gauge needle containing approximately 20 uCi of Ga-67 viewed "end-on" to the camera plane. As discussed in Section 16-3, position co-ordinate signals from each scintillation event in the crystal ultimately appear as X and Y pulses whose amplitude is a function of position. Therefore, an examination of the Y-axis distribution of pulses from the source by the MCA will give a measure of resolution. This can be quantified by determining the full-width at half-maximum (FWHM) of the distribution of gated signals in the Y-direction (say). Hard copies can be made on a chart recorder and the system calibrated by imaging two point sources over a range of known distances apart.

Measurements of resolution were made at each of the 92, 184 and 296 keV photopeaks, with the high and medium energy collimators. These measurements involved centring the energy window of the pulse-height analyzer on each peak (i.e. the standard technique). In a bid to increase sensitivity the energy window for the 92 keV peak was offset to be centred on 97 keV, with an overall range of 82 to 112 keV. This was done to include more of the photopeak whilst avoiding the lead X-rays at 75 keV.

The sensitivity of a collimator/energy window combination is the number of counts registered per unit
activity. Relative sensitivity (in arbitrary units) is given by the area under the spatial distribution curve and this was measured with a planimeter.

Section 16-3-2: Results

Two point sources were mounted vertically in a wax block with a range of separations from 30 mm to 90 mm. Table 16-7 summarizes the results of these measurements, and Figure 16-12 shows the resultant spatial distribution of counts for the 90 mm separation measurements.

Table 16-7 Spatial Distribution Calibration

<table>
<thead>
<tr>
<th>Separation in Space (mm)</th>
<th>Separation on Graph (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>50</td>
<td>41</td>
</tr>
<tr>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>90</td>
<td>75</td>
</tr>
</tbody>
</table>

These values are plotted in Figure 16-13 and the slope of the line of best fit gives the calibration factor of

1 mm (on graph) = 0.83 mm (in space)

The standard technique for choosing the energy range for a given photopeak is to centre the energy window on the peak and then expand the window symmetrically around the centre. The window width is usually expressed in terms
FIGURE 16-12 Spatial distribution of counts for 90 mm separation
FIGURE 16-13  Spatial distribution calibration
of a fraction of the mean energy e.g. a window with a baseline of 100 keV and width of 20% would cover the range 100 keV ± 10% i.e. 90 to 110 keV. The settings used for each of the photopeaks, including the offset window on the 92 keV peak are listed below.

Table 16-8 Energy Window Settings

<table>
<thead>
<tr>
<th>Photopeak (keV)</th>
<th>&quot;Energy Range&quot; Course</th>
<th>&quot;Window Range&quot; Fine</th>
<th>&quot;Window width&quot;</th>
<th>Range of Energy Window (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>100 keV</td>
<td>9.20</td>
<td>20%</td>
<td>83 - 101</td>
</tr>
<tr>
<td>92 (offset)</td>
<td>100 keV</td>
<td>8.70</td>
<td>30%</td>
<td>82 - 112</td>
</tr>
<tr>
<td>184</td>
<td>190 keV</td>
<td>8.80</td>
<td>20%</td>
<td>166 - 202</td>
</tr>
<tr>
<td>296</td>
<td>320 keV</td>
<td>9.80</td>
<td>15%</td>
<td>274 - 318</td>
</tr>
</tbody>
</table>

Figure 16-14 is a typical spatial distribution curve and shows how resolution and sensitivity are determined from the curve. Table 16-9 summarizes the results of resolution and sensitivity measurements.

Table 16-9 Resolution and Sensitivity

<table>
<thead>
<tr>
<th>Photopeak (keV)</th>
<th>FWHM (mm)</th>
<th>Relative Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Energy Collimator</td>
<td>Medium Energy Collimator</td>
</tr>
<tr>
<td>92</td>
<td>9.0</td>
<td>69</td>
</tr>
<tr>
<td>92 (offset)</td>
<td>9.4</td>
<td>70</td>
</tr>
<tr>
<td>184</td>
<td>7.4</td>
<td>33</td>
</tr>
<tr>
<td>296</td>
<td>6.6</td>
<td>8</td>
</tr>
</tbody>
</table>
counts/channel

The high energy collimator is more suitable for 137Cs imaging than a medium energy one, even though the medium energy collimator gave slightly better resolution the advantage of the greater sensitivity of the high energy collimator outweighs this.

With the high energy collimator in use, offsetting the energy window on the 93 keV peak produced an increase in sensitivity but FWHM increased by 6.4% on the other hand, offsetting in conjunction with the 68 keV collimator resulted in an approximately 36% increase in sensitivity but FWHM increased by 0.6% in both cases of offsetting the energy windows there was an increase in background signals outside the walls of the point source.

Most gamma cameras have a single FWHM i.e. they can form images using one peak and in some cases the 18 keV peak should be exploited. As are becoming more common for cameras to be equipped with FWHM the FWHM-280 would be used in this case. The wider we equipped, which allows the use of 67 imaging to be used both the 11 and 18 keV peaks. It also allows the images to be formed of the single 67 peak which could also be exploited in the imaging. However, this would decrease sensitivity by only 20% as compared to using just the 11 and 18 keV peaks with a high energy.

FIGURE 16-14 Typical spatial distribution curve
Section 16-3-3: Discussion

The high energy collimator is more suitable for Ga-67 imaging than a medium energy one. Even though use of the medium energy collimator gave slightly better resolution the advantage of the greater sensitivity of the high energy collimator outweighs this.

With the high energy collimator in use, offsetting the energy window on the 92 keV peak produced no increase in sensitivity but FWHM increased by 0.4 mm. On the other hand, offsetting in conjunction with the energy collimator resulted in an approximately 15% increase in sensitivity but FWHM increased by 0.8 mm. In both cases offsetting the energy window caused an increase in background signals outside the region of the point source.

Most gamma cameras have only a single PHA i.e. they can form images using one photopeak and in these cases the 92 keV peak should be employed. It is now becoming more common for cameras to be equipped with a dual-nuclide adaptor so that a second photopeak can be used for imaging. The GCA-202 used in this research was so equipped, which allows Ga-67 imaging to be done with both the 92 and 184 keV peaks. It also allows images to be formed of the simultaneous distribution of two different radionuclides in the body.

By use of a triple pulse-height adaptor the 296 keV peak could also be included in the imaging. However, this would increase sensitivity by only about 8% (compared to using just the 92 and 184 keV peaks with a high energy...
collimator - see Table 16-9), and this small gain would have to be weighed against the cost ($\sim$10,000) of this specialized piece of equipment.

Section 16-4: Clinical Images

To illustrate the clinical use of these results a series of images were taken of the colon of a patient who had been injected with gallium-67 citrate on the previous day. All images were using both the 92 and 184 keV photopeaks, but with different collimator/analyzer window combinations as follows:

Figure 16-15 a - low energy collimator
b - medium energy collimator
c - high energy collimator
d - high energy collimator, with offset window on 92 keV peak

These pictures were taken by a 35 mm camera attached to the cathode ray tube of the gamma-camera. This is a standard method of obtaining hard copies of nuclear medicine images.

Unfortunately some detail is lost on reproduction, but it is clear that a low energy collimator is clearly unsuitable for use with Ga-67. Use of a medium energy collimator greatly decreases the level of scattered radiation which degrades image quality. This is further improved by imaging with a high energy collimator (Figure
16-15c) where there is the clearest delineation between the "hot" colon and the "cold" background. It should also be noted that the imaging time for Figure 16-15c was only about two-thirds that for Figure 16-15b. Comparison of Figures 16-15c and d shows that offsetting the energy window on the 92 keV peak increases the background counts and thereby decreases the resolution and contrast of the image.
FIGURE 16-15: Ga-67 images (see text)
CHAPTER 17

CONCLUSIONS

The use of the gamma-camera as a diagnostic tool in nuclear medicine was investigated. The role of gallium-67 imaging in particular was reviewed, and the physical principles involved in forming images with this radionuclide were studied. System performance was measured with the parameters resolution and sensitivity, and the following technical factors have been found to provide the optimum blend of resolution and sensitivity in Ga-67 imaging:

i) A high energy collimator should be used. A low energy collimator would allow too much of the higher energy radiation to penetrate the septa, and the sensitivity of the system with a medium energy collimator is not high enough.

ii) The 92 keV photopeak should be employed in imaging. If a dual nuclide adaptor is available, the 184 keV peak should be also used.

iii) The small increase in sensitivity gained by using a triple pulse height adaptor must be weighed against its cost (∼$10,000).
iv) Energy analyzer windows should be centred on the photopeaks. There is no advantage, in terms of resolution or sensitivity, in offsetting the window on the 92 keV peak.

v) To avoid low energy scatter from the lead K X-ray, and to minimise Compton scatter from higher energy peaks, the window on the 92 keV peak should be limited to 20%. The appropriate window for the 184 keV peak is also 20%.
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