Cortico-collicular And Colliculo-collicular Modulation Of The Functioning Of The Superior Colliculus In The Rat

Melvyn Alan Goodale

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FIRE DETECTION WITH ELECTRIC FIELD IN THE SURVEILLANCE AREA

by

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Submitted in partial fulfillment of the requirements for the degree of Master of Engineering Science

Faculty of Graduate Studies
The University of Western Ontario
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ABSTRACT

Ions are produced in our ambient by natural causes (cosmic radiation, radioactive material, etc.), man made equipment normally found in a residential home, and combustion sources. It is known that the concentration of ions in a flame is considerably greater than that of the normal ambient.

An experimental study of the separation of both natural and flame ions under the influence of an electric field was conducted. An "umbrella" type fire detection system which operates on the charge accumulation principle was developed and tested. The complete coverage made possible by this method does not require the use of individual detectors.

Results show that fire detection by the charge accumulation method is feasible.
ACKNOWLEDGEMENTS

The author would like to express his deepest sense of appreciation to Professor I.I. Inculet for his continued guidance and inspiration through the project.

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>xvi</td>
</tr>
<tr>
<td>CHAPTER ONE - INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER TWO - LITERATURE SURVEY</td>
<td>4</td>
</tr>
<tr>
<td>2.1 Survey of Existing Fire Detection Devices</td>
<td>4</td>
</tr>
<tr>
<td>2.1.1 Heat Detecting Devices</td>
<td>4</td>
</tr>
<tr>
<td>Fixed-Temperature Detectors</td>
<td>4</td>
</tr>
<tr>
<td>Rate-of-Rise Detectors</td>
<td>6</td>
</tr>
<tr>
<td>Combined Rate-of-Rise and Fixed-Temperature Detectors</td>
<td>10</td>
</tr>
<tr>
<td>2.1.2 Flame Detecting Devices</td>
<td>12</td>
</tr>
<tr>
<td>2.1.3 Smoke Detecting Devices</td>
<td>14</td>
</tr>
<tr>
<td>2.1.4 Incipient Fire Detectors</td>
<td>16</td>
</tr>
<tr>
<td>2.2 Ambient Ionization</td>
<td>20</td>
</tr>
<tr>
<td>2.2.1 Ions</td>
<td>20</td>
</tr>
<tr>
<td>Sources</td>
<td>21</td>
</tr>
<tr>
<td>Concentrations</td>
<td>25</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Sizes</td>
<td>27</td>
</tr>
<tr>
<td>Mobilities</td>
<td>29</td>
</tr>
<tr>
<td>Combination and Recombination Coefficients</td>
<td>29</td>
</tr>
<tr>
<td>2.2.2 Ion Equilibrium and Life</td>
<td>32</td>
</tr>
<tr>
<td>2.3 Ionization in Flames</td>
<td>36</td>
</tr>
<tr>
<td>2.3.1 Concentration and Distribution of Ions in Hydrocarbon Diffusion</td>
<td>36</td>
</tr>
<tr>
<td>Flames</td>
<td>36</td>
</tr>
<tr>
<td>2.3.2 Mechanisms of Ion Formation in Flames</td>
<td>37</td>
</tr>
<tr>
<td>Thermal Ionization</td>
<td>38</td>
</tr>
<tr>
<td>Ionization via Translational Energy</td>
<td>39</td>
</tr>
<tr>
<td>Cumulative Excitation</td>
<td>40</td>
</tr>
<tr>
<td>Chemi-Ionization</td>
<td>40</td>
</tr>
<tr>
<td>2.3.3 Identification of Ions in Flames</td>
<td>41</td>
</tr>
<tr>
<td>2.3.4 Ionization Produced by Other Types of Fires</td>
<td>41</td>
</tr>
<tr>
<td>CHAPTER THREE - FIRE DETECTION WITH ELECTRIC FIELD IN THE SURVEILLANCE AREA</td>
<td>43</td>
</tr>
<tr>
<td>3.1 General</td>
<td>43</td>
</tr>
<tr>
<td>3.2 Principle of Operation</td>
<td>44</td>
</tr>
<tr>
<td>3.2.1 Measurement of Electric Charge on an Insulated Grid</td>
<td>44</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Charge Accumulation due to Ambient Ions</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Reversal of Electric Field</td>
</tr>
<tr>
<td>3.3</td>
<td>Experimental Work</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Apparatus</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Experimental Procedure</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Results</td>
</tr>
<tr>
<td></td>
<td>Relative Effect on the Rate of Charge Accumulation vs. Time for Varying Conditions of</td>
</tr>
<tr>
<td></td>
<td>Applied Voltage</td>
</tr>
<tr>
<td></td>
<td>Grid Separation</td>
</tr>
<tr>
<td></td>
<td>Candles</td>
</tr>
<tr>
<td></td>
<td>Other Combustibles</td>
</tr>
<tr>
<td></td>
<td>Appliances</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>3.4</td>
<td>Discussion</td>
</tr>
<tr>
<td></td>
<td>Electric Fields</td>
</tr>
<tr>
<td></td>
<td>Leakage Currents</td>
</tr>
<tr>
<td></td>
<td>Candles</td>
</tr>
<tr>
<td></td>
<td>Other Combustibles</td>
</tr>
<tr>
<td></td>
<td>Appliances</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
</tr>
<tr>
<td></td>
<td>Uni-Polar Ion Sources</td>
</tr>
</tbody>
</table>
3.5 Design of Prototype System

3.5.1 Description of System Grid
Timing and Switching
Alarm
Testing
Electric Field
Grid to Ground Capacitance

3.5.2 Operating Results

3.5.3 Possible Uses as a Burglar
Alarm System

CHAPTER FOUR - CONCLUSIONS

CHAPTER FIVE - RECOMMENDATIONS FOR FUTURE STUDY

APPENDIX

1. Variation in Electric Fields

2. One Insulated Cylindrical Conductor
Above Ground

3. Grid to Ground Capacitance

BIBLIOGRAPHY

VITA
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table No.</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Orders of Magnitude of Ion and Condensation Nuclei per Cubic Centimeter</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>Typical Sizes of Atmospheric Ions</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>Average Atmospheric Ion Mobilities Near the Ground</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Median Values of Combination and Recombination Coefficients</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>Results of Prototype Fire Tests</td>
<td>114</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>Model of Detection Device with No Accumulated Charge on Grid Surface</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>Model of Detection Device with Accumulated Charge on Grid Surface</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>Pictorial of Fire Test Chamber Experimental Apparatus</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>Photograph of Fire Test Chamber Experimental Apparatus</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>Rate of Negative Charge Accumulation vs. Time for the Ambient at Various Voltages</td>
<td>57</td>
</tr>
<tr>
<td>6</td>
<td>Rate of Positive Charge Accumulation vs. Time for the Ambient at Various Voltages</td>
<td>58</td>
</tr>
<tr>
<td>7</td>
<td>Rate of Negative Charge Accumulation vs. Time for the Combustion of One Candle at Various Voltages</td>
<td>59</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>8</td>
<td>Rate of Positive Charge Accumulation vs. Time for the Combustion of One Candle at Various Voltages</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>Rate of Ambient Charge Accumulation vs. Time for Different Grid Separations</td>
<td>61</td>
</tr>
<tr>
<td>10</td>
<td>Rate of Negative Charge Accumulation vs. Time for the Combustion of Three Candles</td>
<td>62</td>
</tr>
<tr>
<td>11</td>
<td>Rate of Positive Charge Accumulation vs. Time for the Combustion of Three Candles</td>
<td>63</td>
</tr>
<tr>
<td>12</td>
<td>Rate of Negative Charge Accumulation vs. Time for the Combustion of Various Numbers of Candles</td>
<td>64</td>
</tr>
<tr>
<td>13</td>
<td>Rate of Positive Charge Accumulation vs. Time for the Combustion of Various Numbers of Candles</td>
<td>65</td>
</tr>
<tr>
<td>14</td>
<td>Rate of Negative Charge Accumulation vs. Time for One Candle Ignited at Various Times After Polarity Switching</td>
<td>66</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>15</td>
<td>Rate of Positive Charge Accumulation vs. Time for One Candle Ignited at</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Various Times After Polarity Switching</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Rate of Charge Accumulation vs. Time for Cigarette Smoke</td>
<td>68</td>
</tr>
<tr>
<td>17</td>
<td>Rate of Negative Charge Accumulation vs. Time for the Combustion of One</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Square Foot of Cloth</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Rate of Positive Charge Accumulation vs. Time for the Combustion of One</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Square Foot of Cloth</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Rate of Charge Accumulation vs. Time for the Combustion of Wood</td>
<td>71</td>
</tr>
<tr>
<td>20</td>
<td>Rate of Charge Accumulation vs. Time for the Combustion of a &quot;Kimwipe&quot;</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Disposable Wiper</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Rate of Charge Accumulation vs. Time for the Combustion of Paper</td>
<td>73</td>
</tr>
<tr>
<td>22</td>
<td>Rate of Negative Charge Accumulation vs. Time for a Propane-Air Torch</td>
<td>74</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>23</td>
<td>Rate of Positive Charge Accumulation vs. Time for a Propane-Air Torch</td>
<td>75</td>
</tr>
<tr>
<td>24</td>
<td>Rate of Charge Accumulation vs. Time for a Naptha Gas Lantern</td>
<td>76</td>
</tr>
<tr>
<td>25</td>
<td>Rate of Charge Accumulation vs. Time for a Vaporizer</td>
<td>77</td>
</tr>
<tr>
<td>26</td>
<td>Rate of Charge Accumulation vs. Time for a Hair Dryer</td>
<td>78</td>
</tr>
<tr>
<td>27</td>
<td>Rate of Charge Accumulation vs. Time for a Radiant Heater</td>
<td>79</td>
</tr>
<tr>
<td>28</td>
<td>Rate of Charge Accumulation vs. Time for a Vacuum Cleaner</td>
<td>80</td>
</tr>
<tr>
<td>29</td>
<td>Rate of Charge Accumulation vs. Time for a Positive Ion Generator</td>
<td>81</td>
</tr>
<tr>
<td>30</td>
<td>Rate of Charge Accumulation vs. Time for a Sun Lamp</td>
<td>82</td>
</tr>
<tr>
<td>31</td>
<td>Rate of Charge Accumulation vs. Time for a Toaster</td>
<td>83</td>
</tr>
<tr>
<td>32</td>
<td>Rate of Charge Accumulation vs. Time for a Circulating Fan</td>
<td>84</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>33</td>
<td>Rate of Charge Accumulation vs. Time for a 1500 Watt Hot Plate</td>
<td>85</td>
</tr>
<tr>
<td>34</td>
<td>Rate of Charge Accumulation vs. Time for Boiling Water in an Electric Kettle</td>
<td>86</td>
</tr>
<tr>
<td>35</td>
<td>Rate of Charge Accumulation vs. Time for a Kerosene Lamp</td>
<td>87</td>
</tr>
<tr>
<td>36</td>
<td>Rate of Charge Accumulation vs. Time for a Tesla Coil</td>
<td>88</td>
</tr>
<tr>
<td>37</td>
<td>Rate of Positive Charge Accumulation vs. Time as a Function of Relative Humidity</td>
<td>89</td>
</tr>
<tr>
<td>38</td>
<td>Rate of Negative Charge Accumulation vs. Time as a Function of Relative Humidity</td>
<td>90</td>
</tr>
<tr>
<td>39</td>
<td>Electric Field Plot of Model Fire Test Chamber</td>
<td>92</td>
</tr>
<tr>
<td>40</td>
<td>Theoretical Model of Fire Detecting Device</td>
<td>93</td>
</tr>
<tr>
<td>41</td>
<td>Photograph of Prototype System</td>
<td>104</td>
</tr>
<tr>
<td>42</td>
<td>Photograph of Protection Grid in Environmental Test Chamber</td>
<td>105</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>43</td>
<td>Cramer Multiple Pole Program Cycling Timer</td>
<td>106</td>
</tr>
<tr>
<td>44</td>
<td>Switching Sequence for Prototype System</td>
<td>108</td>
</tr>
<tr>
<td>45</td>
<td>Circuit Diagram of Alarm</td>
<td>110</td>
</tr>
<tr>
<td>46</td>
<td>Electric Field Plot of Prototype Grid System</td>
<td>112</td>
</tr>
<tr>
<td>47</td>
<td>Rate of Charge Accumulation vs. Time for the Prototype System: Ambient Conditions</td>
<td>113</td>
</tr>
<tr>
<td>48</td>
<td>Infinite Cylindrical Conductor above an Infinite Conducting Plane</td>
<td>125</td>
</tr>
<tr>
<td>49</td>
<td>Electric Field as a Function of Time For Various Distances From a Conductor Above Ground</td>
<td>129</td>
</tr>
<tr>
<td>50</td>
<td>System of Two Parallel Wires Above Ground</td>
<td>131</td>
</tr>
</tbody>
</table>
NOMENCLATURE

A  a reactant in a combustion process, mole/cm³

a  radius of conductor used as high voltage grid, meter

B  a reactant in a combustion process, mole/cm³

C  a product in a combustion process, mole/cm³

C_{11}  capacitance of grid conductor to ground, farad

C_{22}  capacitance of grid conductor to ground, farad

C_{12}  capacitance of grid conductor to grid conductor, farad

C_{pg}  capacitance of a person to ground, farad

C_{ga}  capacitance of grid to person, farad

C_{gg}  capacitance of grid system to ground, farad

c  conductivity, mho/meter

D_{1}  electric displacement in insulation of high voltage cable, coulomb/meter²
$D_2$ electric displacement in air gap between high voltage cable and ground, coulomb/meter$^2$.

$D^+$ an ionized product in a combustion process, mole/cm$^3$

$d_1$ thickness of insulation on high voltage cable, meter

$d_2$ separation between high voltage cable and ground, meter

$E_1$ electric field in insulation of high voltage cable, volt/meter

$E_2$ electric field in air gap between high voltage cable and ground, volt/meter

$E_0$ initial electric field established between the grid system and ground, volt/meter

$e$ elementary electronic charge, $1.6 \times 10^{-19}$ coulomb

$\varepsilon_0$ permittivity of free space, $8.85 \times 10^{-12}$ farad/meter

$f$ frequency, hertz

$K$ dielectric constant, unitless

$L$ mean life of an ion, sec
Lₙ  mean life of a small ion, sec
Lₙₑ  mean life of a large ion, sec
N₁  concentration of large positive ions, ions/cm³
N₂  concentration of large negative ions, ions/cm³
N₀  concentration of uncharged condensation nuclei, nuclei/cm³
N  concentration of large ions, the average of N₁ and N₂, ions/cm³
n₁  concentration of small positive ions, ions/cm³
n₂  concentration of small negative ions, ions/cm³
n  concentration of small ions, the average of n₁ and n₂, ions/cm³
n₁₂ combination coefficient for small positive and large negative ions, cm³/sec
n₂₁ combination coefficient for small negative and large positive ions, cm³/sec
n₁₀ combination coefficient for small positive ions and uncharged condensation nuclei, cm³/sec
n₂₀ combination coefficient for small negative ions and uncharged condensation nuclei, cm³/sec
\( \eta \)
combination coefficient for small ions with large ions, the average of \( \eta_{21} \) and \( \eta_{12} \), cm\(^3\)/sec

\( P_1(t) \)
polarization response of the high voltage cable insulation to an applied field, coulomb/meter

\( P_2(t) \)
component of polarization response \( P_1(t) \) that responds practically instantaneously to changes in the internal field and can be characterized by the dielectric constant, \( \varepsilon \), of the insulation, coulomb/meter

\( P_8(t) \)
component of polarization response \( P_1(t) \) that responds slowly to changes in the internal field, coulomb/meter

\( Q_G \)
charge on conductors of grid system, coulomb

\( q \)
production rate of small ions, ion pairs/cm\(^3\) sec

\( r_1 \)
separation between conductors in a 2 conductor grid system, meter

\( r_2 \)
separation between one conductor and the image of the other conductor in a 2 conductor system, meter

\( r_3 \)
distance between a conductor and its image in a 2 conductor grid system, meter
\( r_g \)  \( r_g \) radius of insulated conductor, m

\( V \)  \( V \) applied voltage between the grid system and ground, volt

\( \alpha \)  \( \alpha \) recombination coefficient for small ambient ions, \( \text{cm}^3/\text{sec} \)

\( \vec{a}_y \)  \( \vec{a}_y \) unit vector in \( y \) direction, unitless

\( \alpha_F \)  \( \alpha_F \) recombination coefficient for small flame ions, \( \text{cm}^3/\text{sec} \)

\( \sigma_r \)  \( \sigma_r \) real surface charge density on the high voltage cable insulation, coulomb/meter\(^2\)

\( \Delta Q \)  \( \Delta Q \) change in charge on grid conductors caused by the entrance of a person, coulomb

\( \gamma \)  \( \gamma \) combination coefficient for large positive and large negative ions, \( \text{cm}^3/\text{sec} \)

\( \lambda \)  \( \lambda \) charge per unit length on a conductor, coulomb/meter
CHAPTER ONE

INTRODUCTION

There are four stages of fire: the incipient stage, the smoldering stage, the flame stage, and the heat stage.

The incipient stage is the earliest stage of a fire. Invisible products of combustion are given off and no visible smoke, flame, or appreciable heat are present.

In the smoldering stage, combustion products are now visible as smoke. Flame, or appreciable heat are still not present.

In the flame stage, actual fire exists. Appreciable heat is still not present but follows almost instantaneously.

In the heat stage, uncontrolled heat and rapidly expanding air quickly give rise to a dangerous fire condition.

Almost invariably, it takes much longer for a fire to develop through the first two stages than through the last two. The incipient and smoldering stages can exist for hours and even days before the flame and heat stages are reached, but once flame and heat are present, a fire can accelerate at a rapid rate.

In most fires, only 10% of the products of combustion are in the form of visible smoke; the other 90% are invisible.
More than 95% of the fire detection systems in use today are dependent upon the heat stage of a fire for their operation. However, by the time this heat stage is reached, a dangerous fire condition already exists.

The earliest and most reliable detection of a fire has been proven to be by means of the ionization type fire detector. This is the only type of detector which can detect the invisible products of combustion present in a fire's incipient stage. This type of detector has been performance proved, both in tests and installations, and as a result has gained acceptance as the fastest and most reliable fire detection system available.

Although the ionization detector is the best detector available, its high cost and the necessity of having one in each room make it a more suitable unit for industrial and institutional applications than for residential installations. Furthermore, it will not detect a fire in spaces such as a closet or wall where detector units are not installed. Because of the economic aspect, few residential properties are protected against the hazards of fire; the majority of the residential detection devices installed depend on the fire's heat stage for activation.

The increasing life and property loss due to residential fires warrant a more widespread use of fire detector alarm systems in residential properties. The ideal system should be both efficient and economic.

The principle investigated was that of detecting a fire
under the influence of an electric field. A grid of well insulated high voltage cable is arranged over the volume that is to be protected, analogous to an umbrella. When a voltage is applied between the grid and ground, the electric field produced prevents some of the ions produced in a fire from recombining; the accumulation of these ions on the grid's insulation or on an interposed surface such as the ceiling of a home can be detected by means of a sensitive electrometer. Although a certain level of ambient ionization exists, a fire produces ions in concentrations many magnitudes higher. If recombination can be reduced, a fire can be detected possibly in its incipient stage and certainly in its flame stage.
CHAPTER TWO

LITERATURE SURVEY

2.1 Survey of Existing Fire Detection Devices

2.1.1 Heat Detecting Devices

Heat detecting devices fall into two general categories: those which respond when the detection element reaches a predetermined temperature (fixed-temperature types) and those which respond to an increase in heat at a rate greater than some predetermined level (rate-of-rise types). Some devices combine both the fixed-temperature and rate-of-rise principles. The same principles apply whether the devices are of the spot-pattern type, in which the thermally sensitive element is a compact unit of small area, or the line-pattern type in which the element is continuous along a line or circuit.

Fixed-Temperature Detectors

Thermostats are the most widely used fixed-temperature heat detectors in use today. The common form of thermostat is the bimetallic type which utilizes the different coefficients of expansion of two metals under heat to cause a movement resulting in the closing of electrical contacts. The
bimetallic strip simply operates against a fixed contact, and the distance the strip must travel to close against the contact determines the operating point, or temperature rating, of the thermostat. The usual form of thermostat encountered is the non-adjustable, prerated unit, responsive to heat at its rated temperature. Commercial units are usually set at 135°F or 180°F.

The principle of unequal expansion in a bimetallic assembly is also used in snap-action disc thermostats. The center of the disc is designed to toggle from concave to convex when the temperature at which the device is rated is reached. Disc-type devices develop a greater mechanical force at the point of operation than do ordinary bimetallic strip types.

A major advantage of bimetallic thermostats of both the strip and snap-action disc types is their ability, after operation, to restore to their original condition with a decrease of temperature.

Fixed temperature detection of the line pattern type can be achieved by thermostatic cable. Such cable is a protected assembly of two tensioned steel cables held separated from each other by a heat-sensitive covering applied directly to the wires. At the rated temperature, the covering melts, and the two wires make contact with each other, initiating an alarm. The section of the wire affected by the heat must
be replaced following the melting of the covering.

Another form of a fixed-temperature spot device is the fusible link. Because of their triggering capability, their main use is as a release element for automatically actuating extinguishing equipment.

A fusible link usually consists of two metal parts with a key member held to both of them by a low-melting solder. It is manufactured with various temperature ratings, having about the same range as is found for automatic sprinklers. However, the normal maximum tension is determined by the strength of the parts themselves and is limited by the tendency of the solder to fail by cold flow when subjected to excessive tension.

**Rate-of-Rise Detectors**

Fire detectors that operate on the rate-of-rise principle function when the rate of temperature increase at the detector exceeds a set number of degrees a minute. This range is usually 15°F to 20°F per minute. Detection of this type invariably combines two functioning elements, one of which initiates an alarm on a rapid rise of temperature, while the other acts to delay or prevent an alarm on a slow rise in temperature.

The advantages of the rate-of-rise devices are several. They can be set to operate more rapidly, under most conditions
of combustion propagation, than can fixed-point devices. They are effective across a wide range of ambient temperatures. They recycle rapidly and they tolerate slow increases in the ambient temperature without giving an alarm. However, there is the possibility that they may fail to respond to a fire which propagates very slowly or may be susceptible to false alarms where there is a rapidly increasing ambient temperature that is not the result of hostile combustion.

In a typical pneumatic tubing system operating on the rate-of-rise principle (1), copper tubing (.21 cm. in diameter) is fastened to ceilings or walls in continuous loops and is terminated at both ends in a detector unit or a detector-transmitter. Pressure is built up in the detector diaphragm chamber as heat reaches the tubing and causes the contained air to expand. If the pneumatic system were closed, operation for an alarm would occur when the pressure reached a point, as a result of a temperature increase, where the diaphragm was moved to close an alarm circuit. The system is not closed, however, because a vent is provided which leaks off a portion of the heated air. Proper adjustment of the vent size permits retention of enough pressure to operate the diaphragm, although somewhat later than for the completely closed system. Small changes in the air temperature surrounding the tubing result in small changes in pressures within the tubing and these pressure changes are handled by the vents without
movement of the diaphragm. When the ambient temperature change is rapid, however, the contained air expands so rapidly the vents are incapable of relieving the pressure in the chambers; the diaphragms move and contacts are closed to initiate an alarm.

Instead of a tubing system connected to the releasing mechanism, a pneumatic detecting system may consist of one or more thin-walled, bulb-shaped chambers, known as heat activated devices (HADs), connected to a releasing mechanism by a small diameter tubing system. Up to six HADs may be connected by three-way or four-way fittings to a single tubing line leading to the release. If there are two or more such groups of HADs, each group, and its line of tubing, is connected to the release through a mercury check. Mercury checks are used to prevent pressure produced in the HADs in one group, by the heat of a fire, from being absorbed by the HADs in another group.

A second form of rate-of-rise detector operates on the thermoelectric principle (1). Two sets of thermocouples are commonly mounted in a single housing, so arranged that one set is exposed to convection and radiation while the other is shielded. A voltage is produced when a temperature difference exists between the exposed and unexposed thermo-couple junctions of the detector. The voltage produces a current increase in an electrically supervised circuit,
operating a galvanometer relay, the contacts of which initiate an alarm signal.

By running a cable assembly of four wires through the exposure area, the thermoelectric principle can be applied to line operation. Two wires are of a metal having a high coefficient of thermal resistivity and two having a low coefficient. One of each pair is more fully exposed to heat variations than its mate, and by suitable disposition in a bridge circuit, the variations between the two resistor pairs are translated into an alarm. When the increase in temperature is slow, both the exposed pair and the shielded pair vary resistance at approximately an equal rate, and the bridge stays in balance.

Another type of rate-of-rise detector is the metal expansion type. Its operation is dependent on the unequal expansion rates of two different sizes of metal rods to trigger the release of pilot air or water pressure to any connected pressure-operated mechanism. With slow rates of change in the exposing temperature, the rods expand by approximately equal amounts. With a high rate of temperature change, the smaller rod heats more quickly and expands faster than the larger rod. The difference in the length of the two rods is magnified by a mechanical leverage system to open the pilot air or water valve.

A circuit utilizing the thermistor's negative coefficient of resistance has been described by Lemaire (2). The
device can measure and transmit any rate-of-rise of temperature. The detecting element is a thermistor of small dimensions (2-5 cm. diameter) and the unit is very sensitive over a range of 2-20°C/min. temperature rise.

**Combined Rate-of-Rise and Fixed-Temperature Detectors**

It is common practice to combine the fixed temperature and the rate-of-rise detection principles in the so-called rate-of-rise spot thermostat. This unit is capable of responding to heat from both rapid and slow fires. The typical form which the rate-of-rise thermostat takes is a vented air chamber which heads up in a flexible diaphragm carrying electrical contacts. Heat on the outside of the chamber causes air in the chamber to expand, and when that expansion exceeds the capacity of the vent to relieve the pressure, the diaphragm is flexed to close the electrical contacts it controls. The unit also contains a bimetallic element which causes an alarm when the rated temperature is reached.

Rate compensation devices operate on the rate-of-rise principle but also provide an assured actuation at some predetermined maximum temperature and compensate for changes in rates of temperature rise.

A typical rate compensation device (1) employs a cylindrical outer shell housing struts in compression on which contacts are mounted. The metal of the shell has a
higher coefficient of expansion than the metal of the struts. When the temperature rises, the shell elongates, relieving the compression on the struts and causing the contacts to close. If the rate of temperature rise is low (0-5°F per minute), both the struts and the shell expand, but because of the difference in the coefficients of expansion, the compression on the struts is relieved and the contacts close.

It is important to realize that the operation of a heat sensitive device, such as a fixed-temperature detector or an automatic sprinkler, is dependent on the transfer of heat from the heated air to the device. The rate of which a device will reach its operating point is dependent on a number of factors: (1) the heat transfer coefficient between the device and the heated air, (2) the mass of the device, (3) the surface area of the device, (4) the mass velocity of the air past the device, (5) the temperature difference between the air and the device, and, (6) the rate at which the air itself is being heated during the heat transfer process.

It is readily apparent that when a heat sensitive device operates, the temperature of the surrounding air will always be higher than the operating temperature of the device. This difference between the operating temperature of the device and the actual air temperature is known as thermal lag. Under fire conditions, the difference in the thermal lag between any two given devices is more dependent upon the first five of
the above-mentioned factors than it is upon the sixth. Testing laboratories, therefore, commonly prescribe a maximum of thermal lag.

2.1.2 Flame Detecting Devices

Flame detectors respond directly to the presence of flame. One type senses the infrared radiation emanating from the flames (3) while a second type operates on the ultrasonic doppler principle (4,5).

The first detector is designed to react only to infrared radiation with a small band of frequencies (approximately 2.5-3.5 x 10^8 MHz). Flames with a light temperature of 2000-2500°K have their highest radiation intensity in this selected frequency band: such flames are typical of most fires.

The radiation reaching the detector must be modulated to cause an alarm. The alarm threshold is lowest with a modulation frequency of approximately 12 Hz; a 6 mLux variation of the illumination intensity is sufficient for alarm release. The flickering frequency of open flames is usually between 5 and 25 Hz. At these limits, a 20 mLux variation will suffice to actuate an alarm.

The detector basically consists of a silicon solar cell located behind a convex infrared lens. The voltage generated by the cell is amplified by a 5 stage transistor amplifier-rectifier-integrator circuit. The resulting voltage is used
to actuate a cold cathode tube which drives an alarm relay.

The infrared radiation must be sustained for a certain time interval before the detector will respond. Three, ten, and thirty second delay units are available. Since the radiation must also be modulated, response to constant or short flickering phenomena is excluded.

Although there are many burglar alarm installations which operate on the principle of ultrasonic doppler, methods are being examined to make the detection of fire feasible by this principle. Fires are reflectors of ultrasonics which constitute reflectors because the temperature differences result in acoustic impedance mismatches. The motion of the flames then acts as a multiplicity of moving reflectors which cause doppler frequencies in the presence of an acoustic field. The major problem is the discrimination between fire and other motion.

During the initial development of this system, it was found to be susceptible to false alarms due to the doppler generated by turbulence from convecors, air conditioners, fans, etc. It was determined that the doppler due to turbulence exhibited a 1/f characteristic due to the conservation of momentum in the diffusion process. It was noted that the doppler spectrum due to a fire was more like that due to an intruder than like that due to turbulence. The turbulence problem was met by adding filters and active compensating networks.
Investigation was made towards devising a method of discriminating between an intruder and fire. Tests were conducted to compare the difference between the effects of fire and other motion on the magnitude of the vertically and horizontally propagated dopplers, the degree of waveform asymmetry in the doppler, and the rate of growth of the doppler.

Results have shown that discrimination between fire and intrusion is feasible. The vertical-horizontal doppler ratio method and the use of size and growth characteristics appear most promising.

2.1.3 Smoke Detecting Devices

Photoelectric detection of smoke, in varying degrees of density, has been employed for several years. Three forms of photoelectric detectors are in common use (1): the spot-type detector, the line-type detector and the sampling detector. In each, the change in current resulting from the partial obscuring of a photoelectric beam by smoke between a receiving element and a light source is measured, and an alarm is tripped when this obscuration reaches a critical value. The spot-type unit employs a short beam carried between the source and the receiver in a ceiling-mounted unit, the line-type system employs a beam carried between elements at extreme ends or sides of the protected area, and the sampling detector draws air from one or more protected enclosures, presents
this air to photoelectric scanning at a central point, and initiates an alarm when a critical quantity of smoke appears in the sampling.

One type of spot detector is the reflection type which operates on the Tyndal principle, the reflection of a light source into a photoconductive cell by means of smoke particles. A small chamber, open to the atmosphere, contains a light source and a photoconductive cell so arranged that the beam of light from the light source does not impinge upon the photoconductive cell. When a sufficient quantity of smoke particles from a fire enter the chamber, the light is reflected by the smoke particles into the photoconductive cell. The resistance change of the cell results in an output current increase, a sensitive relay is actuated and an alarm given.

Although all three forms of smoke detectors are designed to meet requirements of sensitivity (6), it must be realized that this sensitivity is very much dependent on natural obscuration of the photoelectric cell, such as that caused by water droplets from highly humid air and dust particles. For this reason, these units usually have the disadvantage of requiring regular maintenance.
2.1.4 Incipient Fire Detectors

The incipient fire detector investigated was the Pyr-A-Larm fire detection system (7,8) manufactured by Pyrotronics, a subsidiary of Baker Industries, Inc. This unit operates on the ionization principle.

Several attempts were made towards the development of a detector which would react to invisible combustion gases as well as smoke, independently of the presence of flames or a rise in temperature.

The ionization chamber was selected as the sensitive element in this device, since the conductivity of air in such an arrangement is a function of the air's chemical and physical composition. However, it was not until the Cerberus Company had developed a highly sensitive three electrode cold cathode gas discharge tube, that it was possible to utilize the principle of the ionization chamber in an arrangement which would provide a practical combustion gas and smoke detector.

The sensitive element of an ionization type detector is an ionization chamber, in which the air is made conductive by the use of an alpha emitter. The air, after being ionized by the alpha particles, is introduced into an electric field; the movement of these ions to the electrodes gives rise to a measurable current.
At low collecting potentials, only part of the ions reach the electrodes. The remainder collide on the way to the electrodes, thus neutralizing each other. It is only when a saturation point potential is reached that all the ions formed reach the electrodes. Beyond this, the current remains virtually constant, regardless of the increase in potential.

Thus, once the saturation point potential is reached, the current in an ionization chamber depends mainly on the composition of the gas between the electrodes. According to the number and size of the gas molecules, more or less ions will be produced. Furthermore, the mobility of the ions is closely related to their size and mass, but there is little difference between gases. Conditions are quite different when the products of combustion enter the ionization chamber. Such combustion gases cause a sharp current drop.

Virtually every combustion process produces particles suspended in high concentration in the air, some of which may be visible as smoke, but most of which are too small to be seen, even though a thousand times larger than an air molecule. These particles hamper the production of ions by increased absorption of the alpha rays and by slower movement in an electric field. The current therefore is decreased through the chamber in two ways. When being ionized themselves, these heavy particles are much less mobile than air molecules; thus their chance of being neutralized before reaching one
of the electrodes is nearly 100%.

Because of the current-potential relationship that exists in an ionization chamber, its equivalent circuit element is considered to be a variable, non-linear resistor. The entrance of combustion gases into such a chamber effectively increases its resistance value, giving rise to a decrease in current. Therefore, the main principle by which fire detection is achieved is the fact that the coagulated combustion particles are considerably larger than air molecules. Such combustion particles are present not only in an open flame but also in the gas and smoke originating from smoldering and overheated materials. However, since combustion gases from a perfect combustion process have molecules closer to the size of air molecules, only a slight current drop is obtained with their presence.

The duration of the current drop is limited. After a sharp drop with the injection of smoke into a closed vessel, the current will return with aging smoke to its original value within a few minutes.

This aging process is due partly to the atmosphere being cleared of the coagulated particles by the electric field, but mainly due to the gradual disintegration of the smaller invisible particles. Only the larger visible smoke particles do not disintegrate. This is why, in a heavy atmosphere of cigarette smoke accumulated over several hours, the detector
will not alarm, while with the same amount of smoke produced in a shorter time, the detector will alarm.

The humidity of the air or other impurities have only a slight influence on the ionization current. The effects of changes of pressure or temperature are largely eliminated by careful choice of dimensions in the chamber construction.

In the design of the Pyr-A-Larm Detector Head, a method of obtaining an alarm signal from the change in current had to be considered. It was decided to transform the current change into a voltage change by means of a series resistance. In place of a linear resistance, the Pyr-A-Larm Detector Head uses a second ionization chamber operating under saturated conditions and which is virtually inaccessible to the atmosphere. Such an arrangement is a constant current device with an extremely high dynamic resistance. Thus any increase in the resistance of the outer or detecting chamber, due to the presence of smoke, will give a greater change of voltage at the junction of the two chambers than that which would occur if a linear resistance were to replace the inner or saturated chamber.

Since the three-electrode cold cathode tube operates on a change in voltage, it was chosen as the triggering unit for the device. The tube is connected in parallel with the inner and outer ionization chambers and the starter electrode is connected to the junction between the two chambers. A rise
in voltage across the outer chamber causes a discharge between the starter electrode and the cathode and hence between the anode and the cathode. The current passing between the anode and the cathode operates an alarm relay, the contacts of which initiate an alarm.

2.2 Ambient Ionization

Chalmers (9) and Schonland (10) have discussed the various aspects of atmospheric electricity. Interest in this paper is concentrated on the ionization of the atmosphere.

2.2.1 Ions

Definition:

Air ions are small particles in the atmosphere, (molecules, groups of molecules, condensation nuclei, or microscopic dust particles), which have an electrical charge acquired through the loss or gain of an electron, or through the adsorption of a molecule which has lost or gained an electron. There are two major types of ions: (1) small ions are formed when an electron is removed from or becomes attached to a gaseous molecule or small cluster of molecules, (2) large ions are electrically charged condensation nuclei.

In general, condensation nuclei appear to consist of some hygroscopic core around which a stable agglomeration of water molecules can form.
Small ions may become large ions by attaching themselves to uncharged condensation nuclei. In addition to the major types of ions, intermediate ions of sizes between the small and the large ions are occasionally observed. Electro-statically charged large haze or dust particles represent ultra large ions. The ultra large ions commonly carry multiple charges, varying from a few to a few hundred elementary charges, either positive or negative. Small, intermediate, and large ions are usually assumed to carry single elementary charges although the existence of multiple charges on large ions has been observed.

Sources

Over land, the production of small ions is chiefly due to radiations from radioactive matter in the earth and air. Approximately one half of the total air ionization is due to radioactive matter in the air, one third is due to radioactive matter in the soil (chiefly radium and thorium), and one sixth is due to cosmic rays (11,12,13).

The ionization due to cosmic rays and radioactive material in the soil is more or less constant for a given geographical area. That due to radioactive matter in the air is subject to variations. The amount of radioactive matter in the air depends upon two factors. First, the rate at which it is dissipated in the atmosphere and secondly, the
rate of exhalation from the soil.

The rate of exhalation is affected by the temperature of the soil, the wind force, the air pressure, the dryness of the soil and the covering of the ground. The rate of dissipation in the atmosphere is governed essentially by the thermal stratification and the motion of the air (11,12).

The production of large ions depends on the availability of condensation nuclei. Sulphuric acid, chloride salts, and the oxides of nitrogen are perhaps the most important chemicals in the air acting as nuclei. Generally, these nuclei are produced wherever substances or processes give off odoriferous fumes, where materials are glowing hot or combustion takes place, whether visible smoke is emitted or not (14,15,16). As a result, large ions are present in great numbers in city air which is polluted by the continual emission of combustion products from chimneys and from automobile exhausts.

There are several ionizers of subordinate importance. Ionization can occur by lightning and point discharges but only occurs in limited regions of the air and for a limited time in stormy weather. Splashing water produces ions because of the Lenard effect but this source is of no great importance except in the neighbourhood of waterfalls or seashores. Other sources include short wave ultraviolet light (mainly at high altitudes), X-rays, hot wires, and drifting sand, dust or snow.

Beckett (17), Skilling and Beckett (18), and Behounek and Kletschka (19), have found that small ion densities in
rooms vary according to occupancy, heat sources, air contamination, and circulation.

In unoccupied rooms, the ion content is not that different from outdoors, but in occupied rooms, the ion content shows a decrease depending on the size of the room and the number of occupants. This loss of ions in occupied rooms appears to be due largely to adsorption by clothing and, to a smaller extent, to respiration and transpiration through the skin (20,21).

Heating sources change ion concentrations. An industrial fan-type heater, at a temperature of 1000°F, was observed by Beckett (17) to increase the concentration of positive ions a hundred times and decrease slightly the concentration of negative ions.

Hot wires, such as platinum and nichrome begin to emit measurable quantities of positive ions when heated above 500-600°C (18,22). Positive ions originate from impurities in the metal filament and are emitted as ions. As the temperature reaches 1000°C, negative ions can be detected. Negative ions, though not emitted, are formed by molecular capture, oxygen molecules in many cases, of electrons, after the electrons have been emitted from the filament. Positive and negative ion concentrations become equal at about 1200°C.

The presence of particulate matter in the air causes a reduction in the concentration of small ions. This decrease
is caused by the union of small ions with the larger uncharged particles, resulting in the formation of large ions.

Small changes in ion concentrations have been observed in rooms supplied with air from ventilation systems. The change in ion content in air supplied through ducts results from the selective absorption of negative ions. These ions have a higher mobility and are lost to the walls by diffusion at a higher rate. Aiding this natural tendency for negative ions to be separated out of air passing through ducts is the natural absorption of negative ions by metal surfaces. However, it has been demonstrated that ionized air can be transported through grounded duct work under reasonably low turbulent conditions for hundreds of feet with relatively low losses (20,23).

A net negative ion density can be produced by an air conditioning system when the water wash system is used. The fine spray causes the formation of many large negative ions by the Lenard effect (19,20).

A main method of producing small ions is by alpha particle emission from a radioactive material such as polonium 210. Such radiation is safe since it is practically free of beta and gamma rays. Such ion sources are widely used because studies suggest that ions in the atmosphere affect health and comfort (24,25,26,27).
Combustion sources, especially flames, produce abundant quantities of ions. These sources will be further investigated in Section 2.3.

Concentrations

The small ion concentration is practically the same over land and ocean although the small ion production is approximately 2 ion pairs/cm³ sec over the sea and 15-20 ion pairs/cm³ sec over the land (11). The difference is caused by the greater concentration of condensation nuclei over the land; the attachment of small ions to large ions of the opposite charge and to uncharged condensation nuclei represents a depletion of small ions.

Concentrations vary from place and time observed; only general magnitudes can be given. Table 1 shows typical ion concentrations.

Near ground level, the concentration of positive ions \(n_1\) and \(N_1\) is slightly greater (10-20%) than that of the negative ions \(n_2\) and \(N_2\). The difference is caused by the earth's electric field (the electrode effect) and the higher combination coefficients of the negative ions which result from their higher mobility.

Ionic content shows regular diurnal and seasonal variations. Generally, the concentration of small ions is highest in the early morning and lowest in the early afternoon.
<table>
<thead>
<tr>
<th>TYPE</th>
<th>LAND</th>
<th>OCEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Ions</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Large Ions</td>
<td>8,000</td>
<td>&lt;1,000</td>
</tr>
<tr>
<td>Condensation Nuclei</td>
<td>20,000</td>
<td>1,000</td>
</tr>
</tbody>
</table>

**TABLE 1: ORDERS OF MAGNITUDES OF ION AND CONDENSATION NUCLEI CONCENTRATIONS PER CUBIC CENTIMETER (11).**
Similarly, the small ion concentration is higher in the summer than the winter.

Gunn (28) and Norinder and Reinhardts (29) have reported variations with meteorological conditions. The small ion concentration is large when visibility is good and when the direction of the wind is from the sea or high mountains.

The concentration is reduced by fog or mist, by an increase in humidity or by land wind, especially from an industrial area. There is a slow rise in the small ion concentrations of both polarities during showers while rapid variations of ion density, especially the negative kind, occur during thunder storms.

The small ion concentration is therefore dependent on two factors. First, the production rate of small ions is directly dependent on the state of the ground. Secondly, the concentration of small ions varies inversely with that of the large ions, which, in turn, depends on the concentration of the condensation nuclei.

Sizes

Types of ions are characterized by a particular size range. Table 2 shows typical size ranges of the various ion types.
<table>
<thead>
<tr>
<th>TYPE</th>
<th>APPROXIMATE DIAMETER (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.001 - 0.005</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0.005 - 0.015</td>
</tr>
<tr>
<td>Large</td>
<td>0.015 - 0.10</td>
</tr>
</tbody>
</table>

**TABLE 2: TYPICAL SIZES OF ATMOSPHERIC IONS (13).**
Mobilities

Ion mobility depends both on the ion and the gas through which it passes. Atmospheric ion mobility is inversely proportional to the density of the air. However, this effect can be neglected near ground level since it is negligible with respect to variations in mobility produced by impurities in the air and particularly by water vapor (11). These two effects increase the mass of an ion and consequently lower its mobility.

Generally, the mobility of a small negative ion is slightly greater than that of a small positive ion. This may be caused by some selective process in the formation of the negative ion or by the negative ion's lower power of adsorption. Table 3 gives average mobilities for the different types of ions.

Combination and Recombination Coefficients

The possibilities of ion coalition may be listed as follows.

1. Small positive ions recombine with small negative ions, thereby producing a neutralization effect. The rate of recombination is proportional to their respective concentrations; the proportionality factor $\alpha$ is the recombination coefficient.
<table>
<thead>
<tr>
<th>TYPE OF ION</th>
<th>CONDITION OF AIR</th>
<th>MOBILITY cm²/sec volt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td>Dry</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Moist</td>
<td>1.1</td>
</tr>
<tr>
<td>Negative</td>
<td>Dry</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Moist</td>
<td>1.2</td>
</tr>
<tr>
<td>Intermediate</td>
<td></td>
<td>5 x 10⁻²</td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td>4 x 10⁻⁴</td>
</tr>
<tr>
<td>Ultralarge</td>
<td></td>
<td>5 x 10⁻⁷</td>
</tr>
</tbody>
</table>

**TABLE 3: AVERAGE ATMOSPHERIC ION MOBILITIES NEAR THE GROUND (11).**
2. Small positive ions combine with large negative ions. This combination causes the destruction of the ions involved and the reconversion of large ions into uncharged condensation nuclei. Here, as in the following processes, the rate of combination varies as the product of the respective concentrations of the particles involved. The proportionality factor $\eta_{12}$ is the combination coefficient.

3. A similar process is the combination of small negative ions with large positive ions. The combination coefficient is $\eta_{21}$.

4. Small positive ions combine with uncharged condensation nuclei. This causes the transformation of small ions into large ions, thus depleting the concentration of small ions and uncharged nuclei but increasing the concentration of large ions. The combination coefficient is $\eta_{10}$.

5. A similar process is the combination of small negative ions with uncharged condensation nuclei with $\eta_{20}$ being the combination coefficient.

6. Large positive ions combine with large negative ions. Neutralization results with the destruction of large ions by pairs and the formation of uncharged nuclei. The total concentration of nuclei (charged and uncharged) is depleted, the size of each nucleus enlarged, and processes 4
and 5 occur, forming large ions of a small mobility. The combination coefficient is $\gamma$.

The coefficients of recombination and combination described are not constant but depend on the mobilities of the large and small ions (9,11). Average values are given in Table 4.

2.2.2 Ion Equilibrium and Life

The change in any ion concentration is the difference between the rates of formation and destruction. Equilibrium exists when this change is zero (9,11).

Small Positive Ions:

$$\frac{dn_1}{dt} = q - an_1n_2 - \eta_{12}n_1N_2 - \eta_{10}n_1N_0$$

At equilibrium:

$$q = n_1(an_2 + \eta_{12}N_2 + \eta_{10}N_0)$$

(1)

Small Negative Ions:

$$\frac{dn_2}{dt} = q - an_1n_2 - \eta_{21}n_2N_0 - \eta_{20}n_2N_0$$

At equilibrium:

$$q = n_2(an_1 + \eta_{21}N_1 + \eta_{20}N_0)$$

(2)

Large Positive Ions:

$$\frac{dN_1}{dt} = \eta_{10}n_1N_0 - \eta_{21}n_2N_1 - \gamma n_1N_2$$
<table>
<thead>
<tr>
<th>COEFFICIENT</th>
<th>MEDIAN VALUE cm$^3$/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\eta_{12}$</td>
<td>$2.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\eta_{21}$</td>
<td>$4.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\eta_{10}$</td>
<td>$0.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\eta_{20}$</td>
<td>$1.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$\approx 10^{-9}$</td>
</tr>
</tbody>
</table>

**TABLE 4: MEDIAN VALUES OF COMBINATION AND RECOMBINATION COEFFICIENTS (17).**
At equilibrium:
\[ n_{10}N_0 = n_{21}n_2N_1 + \gamma N_1N_2 \] (3)

Large Negative Ions:
\[ \frac{dN_0}{dt} = n_{20}n_2N_0 - n_{12}n_1N_2 - \gamma N_1N_2 \]

At equilibrium:
\[ n_{20}n_2N_0 = n_{12}n_1N_2 + \gamma N_1N_2 \] (4)

Over oceans and at high altitudes, assume the absence of condensation nuclei. Let \( n_1 = n_2 = n \).

Then, equations 1 and 2 become:
\[ n = \sqrt{\frac{q}{a}} \] (5)

Over land, assume \( N_1, N_2, N_0 > n_1, n_2 \).

Then, equations 1 and 2 become:
\[ q = n_1(n_{12}N_2 + n_{10}N_0) \]
\[ = n_2(n_{21}N_1 + n_{20}N_0) \] (6)

Using the equation balance to be developed for large ions:
\[ q = 2n_1n_2n_{12} \]
\[ = 2n_2N_1n_{21} \] (7)
If $N_1$ is assumed equal to $N_2$ and $q$ is constant, then the concentration of small ions is inversely proportional to the concentration of large ions of the same polarity.

In equations 3 and 4, the $\gamma N_1 N_2$ term is negligible by comparison to the other terms if the air is not highly polluted.

Then:

$$n_1 n_1 N_0 = n_2 n_2 N_1$$  \hspace{1cm} (8)

$$n_0 n_2 N_0 = n_1 n_2 N_2$$  \hspace{1cm} (9)

Substitution of these results gives equation 7.

The mean life, $L$, of an ion is the time interval between the formation and the destruction of the average ion (11).

$$L = \frac{\text{existing ion concentration}}{\text{ion production rate}}$$

For small ions in clean air, substitution of equation 5 into $L_n = \frac{n}{q}$ yields:

$$L_n = \frac{1}{an}$$

Therefore, the mean life of a small ion in clean air is of the magnitude of 5-10 minutes.
For polluted air over land, substitution of equation 7 yields:

\[ L_n = \frac{1}{2\eta N} \]

This equation gives a lifetime of a few seconds to a minute.

For large ions, substitution of equation 7 or 8 yields:

\[ L_N = \frac{1}{\eta n} \]

For very polluted air, substitution of equation 3 or 4 yields:

\[ L_N = \frac{1}{\eta n + \gamma n} \]

Large ions have a mean life of 10 minutes or more.

2.3 Ionization in Flames

2.3.1 Concentration and Distribution of Ions in Hydrocarbon Diffusion Flames

Most hydrocarbon oxygen or hydrocarbon air flames produce ions in the range \(10^{10} - 10^{12}\) ions/cc (30,31,32,33).
The major ionization in a flame occurs in a very thin zone, corresponding to the reaction zone. In the hot gases immediately after this zone, the ion concentration is much reduced because of ion removal processes. For diffusion flames at atmospheric pressure, dissociative recombination is the predominant factor (33,34).

As is the case for ambient ions, the rate of recombination of positive and negative flame ions is proportional to their concentrations, the proportionality factor is \( \alpha_P \), the recombination coefficient. Measurements have shown this coefficient to be inversely proportional to temperature, independent of pressure and of the order of magnitude of \( 10^{-7} \text{ cm}^3/\text{sec} \) (33,35).

Experiments have shown that the maximum ion concentration with respect to composition occurs close to stoichiometric (33,36). Furthermore, Calcote (33) has shown that the equivalence ratio is more significant in determining ion concentrations than the flame temperature.

2.3.2 Mechanisms of Ion Formation in Flames

Several methods have been suggested to explain the production of ions in flames (35,37,38). H.F. Calcote (32) described the following possible mechanisms: thermal ionization, ionization via translational energy, cumulative excitation, and chemi-ionization.
Thermal Ionization

The most obvious source of ions is thermal, i.e., equilibrium ionization determined by the concentrations of species of low ionization potential and the flame temperature. The equilibrium constant for this process was derived by Saha in 1920.

Thus by means of straightforward thermodynamics employed to calculate the adiabatic flame temperature and equilibrium concentrations in a flame, it is possible to calculate the equilibrium concentrations of ions.

There are several possibilities for ionization by thermal means. These are: (1) ionization of impurities, (2) equilibrium species existing at flame temperature, (3) non-equilibrium species existing at the flame temperature and, (4) carbon particles.

(1) Impurities

Any impurities having low ionization potentials such as the alkali metals or alkaline earths will contribute to ionization, particularly at higher temperatures. The major ionization in a flame occurs in the reaction zone; this is sufficient proof in itself that ionization is not due to impurities because the gas temperature remains high past the reaction zone and in fact usually rises slightly. If impurities were responsible for the majority of ions, the
ion concentration would follow closely to the gas temperature but it does not, and the ion concentration falls rapidly.

(2) and (3) Reaction Intermediates and Products

Reaction intermediates and products either present in equilibrium or non-equilibrium concentrations might contribute to ionization. However, these mechanisms will not account for all the ionization in the flame front of hydrocarbon flames. The required species concentrations to produce thermally the experimental ion concentrations in flames are much larger than possible.

(4) Carbon Particles

The concentration of ions in the luminous part of a diffusion flame, where the carbon particles are present, is less than at the base of the flame where luminous particles have not yet formed. This experimental evidence reduces the importance of ionization by carbon particles. Although experimental evidence is weak, ionization of carbon particles is certainly a possibility in high temperature flames where copious quantities of carbon are produced.

Ionization via Translational Energy

This theory suggests that the total energy of the combustion process is released in the form of kinetic energy of translation. It is assumed that, before this energy can reach equilibrium with the rotational and vibrational degrees of
freedom, ions are produced by collisions of fast-moving neutral species and that the ions so formed persist to build up a high concentration. However, there are several serious difficulties with the concept of ionization in flames via translational energy.

First, a classical treatment of ionization by collision of neutral species considering the conservation of energy before and after collision shows that only about one half of the kinetic energy is available for ionization. Secondly, for the ionization by collision of neutral species, the efficiency of ionization increases very slowly with increasing energy of collision partners above the threshold energy for ionization. It would seem that any simple mechanism by which energy is first released as translational energy and then produces ionization is inefficient.

**Cumulative Excitation**

It is certainly reasonable to suppose that an electronically excited species might undergo a number of elastic collisions before finding the proper partner with which to react. Thus, collisions of the second kind where the excitation energy of one atom or molecule is transferred to another to cause ionization might be a reasonable source of ions.

**Chemi-Ionization**

In chemi-ionization, the energy of an elementary exothermic chemical reaction leaves one of the products in
an ionized state.

\[ A + B + C + D^+ + e \]

This is equivalent to stating that as a chemical reaction moves over a potential energy surface, it crosses over an excited (actually ionized) potential energy surface of the products. This theory has been preliminarily investigated by Calcote (33) and since only the chemi-ionization and cumulative excitation theories fit experimental observations, it is felt that they are the two major ion producing mechanisms.

2.3.3 Identification of Ions in Flames

Much work has been done on the identification of both positive and negative ions found in flames (36, 39, 40, 41). Although relative concentrations vary from one type of flame to another, \( \text{H}_3\text{O}^+ \) and \( \text{C}_2\text{H}^- \) are among the most abundant positive and negative ions respectively. The negative ion is believed to be produced by electron attachment (32).

2.3.4 Ionization Produced by Other Types of Fires

Little information is available concerning the ionization found in incipient and smoldering fires. Certainly, where flame and smoke are present together, the majority of
the smoke particles will become charged by combination with the small ions produced in the flame. For example, cigarette smoke is considered the most effective deionizer indoors (42). The high concentration of smoke particles quickly increases the number of large ions and decreases the number of small ions.

Quon (15) has shown that condensation nuclei are formed in the incipient fire, before the formation of smoke particles. Quon et al (43) reported that a higher concentration of nuclei is found in poor combustion sources (43). It has been observed that up to 74% of the condensation nuclei in tobacco smoke are charged (15).

Therefore, experimental evidence has shown that ions are certainly present in hydrocarbon diffusion flames, in concentrations as high as $10^{12}$ ions/cc in the reaction zone. Identification of these ions has been achieved and the theories of chemi-ionization and cumulative excitation appear to best explain ion formation.
CHAPTER THREE

FIRE DETECTION WITH ELECTRIC FIELD

IN THE SURVEILLANCE AREA

3.1 General

Referring to the review of the different types of existing fire detection devices, we have seen that:

(a) Heat detectors detect a fire only after it has progressed to the heat stage; a dangerous fire condition usually exists at this stage. The advantage of heat detectors is their relatively low cost.

(b) Flame detectors rely on the fire's flame stage for operation. Such systems are relatively complex and expensive and usually operate with a delay after the appearance of flame.

(c) The smoke detectors available are useful only for fires in which copious amounts of smoke are present; they are ineffective for rapidly developing fires.

(d) The incipient fire detector, although the best detector available, is limited in its applications by its cost. It certainly is not practical for residential installations.
It was thought that by covering the surveillance area with a grid of insulated cable and applying a voltage between this grid and ground, an electric field could be produced which will be present throughout the protected volume. Free ions are attracted to and collected on the insulation of the high voltage cable or on any interposing surface such as a ceiling. The accumulation of these charges can be measured by an electrometer.

When a flame source is existent in the surveillance area, the rate of charge accumulation will increase. The electric field, although weak, prevents a certain proportion of the abundant flame ions from recombining and attracts them to the insulated grid.

One of the advantages of this system is the complete coverage provided of a large volume. This eliminates the necessity of having expensive sensors in each room of a home. Coverage of the volume inside walls again emphasizes the effectiveness of this "umbrella" type sensor. The application of this system to residential property protection appears worthwhile.

3.2 Principle of Operation

3.2.1 Measurement of Electric Charge on an Insulated Grid

Consider the much simplified model of the fire detection system as shown in figure 1. At time \( t = 0 \), the high voltage
FIGURE 1: MODEL OF DETECTION DEVICE WITH NO ACCUMULATED CHARGE ON THE GRID SURFACE
supply is switched on and almost instantaneously, an amount of charge, \( Q_g = C_{gg} V \), is established on conductor \( A \), where \( C_{gg} \) is the capacitance of the conductor to ground and \( V \) is the applied voltage, with polarity as shown. The electric field, \( E_0 \), established between the upper insulated conductor and ground draws ambient negative ions to the upper insulated conductor and ambient positive ions to the ground. As the negative ion arrives on the insulation and is held there by the electrostatic force, it induces a positive charge on the conductor, i.e., an electron goes to ground and the electrometer effectively measures the negative charge that has accumulated on the insulation. The negative ions continue to accumulate on the insulation of the upper conductor while positive ions continue to go to the ground.

It might happen that some accumulated charge is removed from its position on the insulation due to impact by other negative ions, air turbulence, etc. This does not matter if the electrometer is measuring net charge accumulation; the net charge will still be negative. However, if current were being measured, the temporary loss of accumulated charge would result in a reversal of the current direction.

The system is therefore effective when measurements are made of the net charge accumulation; current measurements would fluctuate and be meaningless.
3.2.2 Charge Accumulation Due to Ambient Ions

Using a system as shown in Figure 1, negative ambient ions continue to accumulate on the insulation of the upper conductor while positive ambient ions continue to go to the ground. Since the concentrations of ambient ions are low, it would take a relatively long period of time before a large quantity of charge would accumulate on the insulation of the upper conductor.

Figure 2 gives a qualitative observation of the system after a time interval of approximately an hour. The large amount of accumulated charge will have reduced the strength of the electric field that the free negative and positive ions are subject to. After a very long time interval such as 2 or 3 days, practically all the electric field will have become concentrated between the conductor and the surface of the insulation. As a result, the accumulated charge measured in any interval of time will have become very small since most of the charge that will be measured then will be the leakage through the insulation.

Consequently, a sudden increase in the concentration of the ions in the protected volume would not be detected by the electrometer system.
FIGURE 2: MODEL OF DETECTION DEVICE WITH ACCUMULATED CHARGE ON THE GRID SURFACE
3.2.3 Reversal of Electric Field

To make the system efficient at all times, the polarity of the high voltage is switched periodically. In the model considered in Figures 1 and 2, the polarity reversal would cause the accumulated negative charge to be repelled from the insulation. The electric field would then become effective in drawing positive ions to the negative polarity upper insulated conductor and negative ions to the ground.

Under these conditions of polarity switchings, any sudden increase in the concentration of ions in the surveillance area will result in an increase in the accumulation of charge per unit time on the upper grid's insulation. The sensitivity of the electrometer is chosen so that only a very large increase in ionization, i.e. due to combustion, is detected.

Since the rate of charge accumulation is being measured on the upper insulated conductor, large initial levels will be observed each time the polarity of the voltage is switched. The explanation is as follows.

Suppose the upper grid has been operating at a positive potential with respect to ground. Negative charged ions will have accumulated on the insulation, as shown in Figures 1 and 2. When the polarity is switched so that the grid is now at a negative potential with respect to ground, these charged ions will be repelled from the insulation. This will be seen
by the electrometer as being equivalent to the accumulation
of positive charge. A large initial charge accumulation
level will therefore be measured each time the polarity of
the voltage supply is switched.

3.3 Experimental Work

3.3.1 Apparatus

The following is a list of the apparatus used in the
experimental testing.

1. Electrometer, Keithley Instruments Model 602.
   Input resistance $>10^{14}$ ohms, shunted by 20 pf.
   Accuracy: $\pm5\%$ full scale on all ranges.

2. High Voltage D.C. Supplies, Lambda Electronics
   Corporation, 0-525 V.D.C.

3. High Voltage Cable, Alpha No. 1665.

4. Voltmeter, Avometer Model MK. III.

5. Portable Relative Humidity and Temperature
   Indicator, Honeywell Model No. W611A.

6. Constant Voltage Transformer, Sola Type CVS.
   118 V. secondary (±1V) for 95-130 V primary.

7. Vacuum Cleaner, Hoover Model No. 916.


10. 1500 Watt Hot Plate, Force Electric Products, Model No. 866-D.

11. Positive Ion Generator, Wesix Electric Heater Company, Model No. MK IV.


15. Fan, Rotor Electric Company, Model 60T.

16. Electric Kettle, General Electric, Model K43C.

17. Naptha Gas Lantern, Coleman.

18. Hair Dryer, Kenmore, Model No. 3078775.

19. Stop Watch, Leonidas, Model No. 8042.

20. Candles, Large 12 in. type.

21. Analog Field Plotter, Sunshine, Model No. 24-1.

3.3.2 Experimental Procedure

A fire test chamber framework, of dimensions 0.86m. x 0.86m. x 0.92m. was constructed of acrylic plastic. Teflon insulated high voltage cable was secured to this framework with electrical tape, thus forming an upper and lower grid system, the separation of which was adjustable. A high voltage D.C. supply, operated from regulated line voltage, was connected between the upper and lower grids, thus providing an electric field between the same. Charge accumulation on the upper grid was measured by means of an electrometer operating off-ground. The Keithley Instruments Model 602 Solid State Electrometer could be safely operated up to 1500 volts off ground with the case grounded. The upper grid was connected to the electrometer's high impedance terminal by a shielded lead of Amphenol RG-58A/U coaxial cable. The electrometer's low impedance terminal was connected to the high voltage supply by teflon insulated high voltage cable. A similar connection was made from the supply to ground. The electrometer case was also grounded. The connection between the upper grid and the electrometer input lead was well insulated with Dow Corning Silastic 731 RTV. The experimental apparatus is shown in Figures 3 and 4.

The experimental testing was conducted in the 1.8m. x 1.5m. x 2.4m. shielded High Vacuum Electrostatics Research Room situated in the Electrostatics Research Laboratory. The
FIGURE 3: PICTORIAL OF FIRE TEST CHAMBER
EXPERIMENTAL APPARATUS
fire test chamber and the electrometer were situated on an acrylic box and wooden table, the box being supported by the table. The power supplies were situated on recessed racks in one corner of the shielded room.

Measurements of the charge accumulation due to ambient ionization, combustion ionization, and the operation of various appliances were taken at various voltages (0-1000 V.D.C.) and grid separations (0.15m, 0.6m, and 0.9m). These charge accumulations were measured over various time intervals by means of a stop watch accurate to 0.1 seconds, and converted to "equivalent" currents. An equivalent current was defined as the accumulated charge divided by the time interval over which it was measured.

3.3.3 Results

The results of the tests done in the model fire test chamber are shown in Figures 5 to 38.

The relative effect of various conditions on the rate of charge accumulation vs. time is shown in the figures as follows.

<table>
<thead>
<tr>
<th>Condition Investigated</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Voltage</td>
<td>5-8</td>
</tr>
<tr>
<td>Grid Separation</td>
<td>9</td>
</tr>
<tr>
<td>Candles</td>
<td>10-15</td>
</tr>
<tr>
<td>Other Combustibles</td>
<td>16-23</td>
</tr>
</tbody>
</table>
Appliances 24–36

Relative Humidity Changes Caused by Boiling Water in an Electric Kettle 37–38
FIGURE 5: RATE OF NEGATIVE CHARGE ACCUMULATION VS. TIME FOR THE AMBIENT AT VARIOUS VOLTAGES
FIGURE 6: RATE OF POSITIVE CHARGE ACCUMULATION VS. TIME FOR THE AMBIENT AT VARIOUS VOLTAGES
FIGURE 7: RATE OF NEGATIVE CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF ONE CANDLE AT VARIOUS VOLTAGES
SEPARATION: 0.6 M.

LEGEND

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>VOLTAGE, V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>250</td>
</tr>
<tr>
<td>●</td>
<td>500</td>
</tr>
<tr>
<td>□</td>
<td>750</td>
</tr>
<tr>
<td>■</td>
<td>1000</td>
</tr>
</tbody>
</table>

FIGURE 8: RATE OF POSITIVE CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF ONE CANDLE AT VARIOUS VOLTAGES
Figure 9: Rate of Ambient Charge Accumulation vs. Time for Different Grid Separations
FIGURE 10: RATE OF NEGATIVE CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF THREE CANDLES

SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

○ 3 CANDLES
● AMBIENT
Figure 11: Rate of positive charge accumulation vs. time for the combustion of three candles.

Separation: 0.6 m.
Voltage: 1000 V.

- 3 candles
- Ambient
FIGURE 12: RATE OF NEGATIVE CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF VARIOUS NUMBERS OF CANDLES
FIGURE 13: RATE OF POSITIVE CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF VARIOUS NUMBERS OF CANDLES
Figure 14: Rate of negative charge accumulation vs. time for one candle ignited at various times after polarity switching.
SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

FIGURE 15: RATE OF POSITIVE CHARGE ACCUMULATION
VS. TIME FOR ONE CANDLE IGNITED AT
VARIOUS TIMES AFTER POLARITY SWITCHING
FIGURE 16: RATE OF CHARGE ACCUMULATION VS. TIME FOR CIGARETTE SMOKE
FIGURE 17: RATE OF NEGATIVE CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF ONE SQUARE FOOT OF CLOTH
SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

- FLANNELETTE
- COTTON
- MARQUISETTE

FIGURE 18: RATE OF POSITIVE CHARGE ACCUMULATION
VS. TIME FOR THE COMBUSTION OF ONE SQUARE FOOT OF CLOTH
FIGURE 19: RATE OF CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF WOOD
FIGURE 20: RATE OF CHARGE ACCUMULATION VS.
TIME FOR THE COMBUSTION OF A
"KIMWIPE" DISPOSABLE WIPER
FIGURE 21: RATE OF CHARGE ACCUMULATION VS. TIME FOR THE COMBUSTION OF PAPER
FIGURE 22: RATE OF NEGATIVE CHARGE ACCUMULATION VS. TIME FOR A PROPANE-AIR TORCH
FIGURE 23: RATE OF POSITIVE CHARGE ACCUMULATION VS. TIME FOR A PROPANE-AIR TORCH
FIGURE 24: RATE OF CHARGE ACCUMULATION VS.
TIME FOR A NAPTHA GAS LANTERN

SEPARATION: 0.6 M.
VOLTAGE: 1000 V.
FIGURE 25: RATE OF CHARGE ACCUMULATION VS. TIME FOR A VAPORIZER
FIGURE 26:  RATE OF CHARGE ACCUMULATION VS. TIME FOR A HAIR DRYER
SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

NEGATIVE
POSITIVE
AMBIENT

FIGURE 27: RATE OF Charge ACCUMULATION VS. TIME FOR A RADIANT HEATER
FIGURE 28: RATE OF CHARGE ACCUMULATION VS. TIME FOR A VACUUM CLEANER

SEPARATION: 0.6 M.
VOLTAGE: 1000 V.
FIGURE 29: RATE OF CHARGE ACCUMULATION VS. TIME FOR A POSITIVE ION GENERATOR
FIGURE 30: RATE OF CHARGE ACCUMULATION VS. TIME FOR A SUNLAMP
FIGURE 31: RATE OF CHARGE ACCUMULATION VS. TIME FOR A TOASTER

SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

- □ NEGATIVE
- ● POSITIVE
- ○ AMBIENT
FIGURE 32: RATE OF CHARGE ACCUMULATION VS. TIME FOR A CIRCULATING FAN
SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

○ POSITIVE
● NEGATIVE

FIGURE 33: RATE OF CHARGE ACCUMULATION VS. TIME FOR A 1500 WATT HOT PLATE
FIGURE 34: RATE OF CHARGE ACCUMULATION VS. TIME FOR BOILING WATER IN AN ELECTRIC KETTLE

SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

- POSITIVE
- NEGATIVE

BOILING BEGINS, VISIBLE STEAM
REMOVAL OF KETTLE
FIGURE 35: RATE OF CHARGE ACCUMULATION VS. TIME FOR A KEROSENE LAMP
FIGURE 36: RATE OF CHARGE ACCUMULATION VS. TIME FOR A TESLA COIL
FIGURE 37: RATE OF POSITIVE CHARGE ACCUMULATION VS. TIME AS A FUNCTION OF RELATIVE HUMIDITY
SEPARATION: 0.6 M.
VOLTAGE: 1000 V.

RELATIVE HUMIDITY
- 10-20%
- 30-40%
- 50-60%

HUMIDITY CHANGED BY
BOILING WATER IN AN
ELECTRIC KETTLE

FIGURE 38: RATE OF NEGATIVE CHARGE ACCUMULATION
VS. TIME AS A FUNCTION OF RELATIVE
HUMIDITY
3.4 Discussion

Electric Fields

Figure 39 shows an electric field plot, done by means of an analog field plotter, of the two grid system inside the shielded enclosure, for a grid separation of 0.6 meter. The electric field is fairly uniform between the two grids, where all the experiments were done. The approximate value of the field strength is 600 volt/meter for an applied potential of 1000 volts. Field plots were also done for other grid separations but showed only small variations in the electric field between the grids. The strongest field is concentrated between the upper grid and the top of the shielded enclosure. This was confirmed from Figure 9. For the measurement of the ambient ionization at various grid separations, the equivalent currents varied little.

For considering the variations in the electric fields caused by charge accumulation, two simplified models of the system will be discussed.

a) A very closely spaced grid of insulated conductors which may be approximated by an insulated plate.

b) One insulated cylindrical conductor situated above ground.

The experimental grid, shown in Figures 3 and 4, represents an intermediate case with 4 insulated cylindrical conductors.
FIGURE 39: ELECTRIC FIELD PLOT OF MODEL FIRE TEST CHAMBER

EXPERIMENTS CONDUCTED IN SHADED REGION
FIGURE 39: ELECTRIC FIELD PLOT OF MODEL FIRE TEST CHAMBER

EXPERIMENTS CONDUCTED IN SHADED REGION
FIGURE 40: THEORETICAL MODEL OF FIRE DETECTING DEVICE
a. The Closely Spaced Grid Above Ground

A diagram of this model is shown in Figure 40. The parameters of interest are $E_1$ and $E_2$, the electric fields in the insulation and in the air gap respectively.

Calculation of Electric Fields (44,45).

1. Apply the line integral law

$$d_1 E_1 + E_2 d_2 = V$$

2. Apply Gauss' Law

$$D_1 - D_2 = \sigma_r$$

3. By definition

$$D_1 = P_1 + \varepsilon_0 E_1$$

4. $P_1(t) = P_i(t) + P_s(t)$

5. $P_i(t) = \varepsilon_0 (K-1) E_1(t)$

6. In the air gap, $P_s(t) = 0$

7. $D_2 = \varepsilon_0 E_2$

Combining 3, 4, and 5 gives:
8. \[ D_1 = K\epsilon_0 E_1 + P_s \]

Combining 1, 2, 7, and 8 yields:

\[ E_2 = \frac{KV - (\frac{\sigma_r - P_s}{\epsilon_0}) d_1}{d_1 + Kd_2} \]

and

\[ E_1 = \frac{V}{kd_2 + d_1} + \frac{(\sigma_r - P_s)d_2}{\epsilon_0(kd_2 + d_1)} \]

where \((\sigma_r - P_s)\) is the net surface charge density.

These calculations indicate that the electric fields and correspondingly, the equivalent currents are dependent on the grid voltage applied and the accumulated charge. This is confirmed in Figures 5 and 8.

Calculations, shown in Appendix 1, yield numerical approximations for the electric fields, \(E_1\) and \(E_2\), of 780 volt/meter and 1640 volt/meter respectively. These are the values assuming \(\sigma_r = 0\). Further calculations show that, with normal ambient ionization, the fields \(E_1\) and \(E_2\) change to 1463 volt/meter and 1637 volt/meter respectively after only 10 seconds. These changes are the result of accumulated charge, \(\sigma_r\), on the grid insulation.
b. One Insulated Cylindrical Conductor Above Ground

Calculations shown in Appendix 2 indicate that, with the assumption that the ambient ions continue to accumulate on the surface of the insulation at the same rate, the electric field at the surface of the insulation decays rapidly from an initial value of $9.0 \times 10^4$ V/m to a final value of zero in approximately 10 minutes. Calculations in Appendix 2 also show that the values of the electric fields at points more distant from the conductor decrease less rapidly with time.

By a rough extrapolation of the results of ambient experiments conducted with the 4 wire grid (see Figures 5 and 6), it is estimated the electric current and hence the field will be reduced to zero in approximately 1 hour.

**Leakage Currents**

Consider the decay of the surface charge under the effect of the internal field, $E_I(t)$. Ohm's law for the decay of the real surface charge because of the volume conductivity $c$, under the effect of the internal field $E_I(t)$ is given by the following expression.
\[ \frac{d\sigma_r}{dt} = -\sigma E_1(t) \]

For Teflon \( \sigma = 10^{-15} \) mho/meter.

\[ \therefore \frac{d\sigma}{dt} = -10^{-15} E_1(t) \text{ coulomb/sec}. \]

Therefore, leakage currents of the order of \( 10^{-12} \) amperes result when the internal field approaches \( 10^3 \) volt/meter.

To make the detection of ions efficient, voltage polarity switching is necessary. As the charge accumulates on the insulation of the high voltage grid, the collecting field \( E_2(t) \) decreases, making the system less sensitive to any increase in ionization. By reversing the voltage polarity, the accumulated charge is removed from the grid and \( E_2(t) \) is increased.

Candles

The initial equivalent current increased approximately 10 times for each candle that was burnt. However, the levels were approximately the same after 2 or 3 minutes, as shown in Figures 12 and 13. Furthermore, the decay of the equivalent current is more rapid when combustion sources, such as candles, were introduced into the surveillance area. This showed that the accumulated charge on the upper grid's insulation had effectively decreased the electric field in the air gap. As a result, recombination of the flame ions was no longer being
prevented and the collection of these ions was much reduced.

The initial current level progressively dropped for longer time intervals between the voltage polarity switching and the candle's introduction into the surveillance area. These decreased initial current levels show that the electric field strength had decreased due to the ambient ionization, making the system less sensitive to a sudden increase in ionization. The number of ions collected is dependent on the electric field strength in the air gap between the grids.

It is important to note from Figures 5 and 6 that the ambient charge accumulation on the high voltage grid comes not only from the space between the grids but also from the entire volume of the shielded room. The electric field plot shown in Figure 39 confirms this. However, with flames, the majority of the charge separation takes place between the two grids.

The high initial levels of the charge accumulation rates show the system's high sensitivity immediately after the voltage polarity is switched. This electric field reversal drives accumulated charge from the high voltage grid and attracts ions of the other polarity to it. As soon as charge begins to accumulate on the grid, the sensitivity of the system decreases because of lower electric field strengths.
Other Combustibles

The large increases in the charge accumulation rates for the combustion of cloth, wood, paper, and "Kimwipe" disposable wipers indicate that these combustion sources are suppliers of large quantities of ions of both polarities.

Cigarette smoke might be expected to give a larger increase in the charge collected than was observed in Figure 16. However, because of the large size of smoke particles, cigarette smoke is generally considered one of the most effective deionizers inside a room (42). Even though charged, cigarette smoke particles have such a low mobility that their velocity is very low in the weak electric fields used. As a result, few smoke particles will be detected.

The results of tests conducted with an air-propane torch, as shown in Figures 22 and 23, indicate that initial equivalent current levels increase with flame size. The rapid decay of the current within the first 2 minutes indicates that the accumulated charge has reduced the collecting field strength. The necessity for voltage polarity switching is again apparent.
Appliances

Charge accumulation rates did not vary from the ambient level with the presence of a vaporizer, vacuum cleaner, sunlamp, and a circulating fan.

It would be expected that a sunlamp would produce an increase in the charge accumulation rate. However, it has been shown that an ultraviolet light source produces ions by the interaction of the light on the metal housing surrounding the bulb (21).

This would suggest that the metal housings are made of a metal with a relatively high work function to reduce electron emission and the possibility of ozone production.

The effects of appliances that used resistance heating gave interesting results. These include the hair dryer, the 1500 watt hot plate, the toaster, and the radiant heater. Small or negligible increases in the negative ion accumulation rates and small to moderate increases in the positive ion accumulation rates suggest that these appliances use different types of heater wire and operate at different temperatures. It is known that certain metals, such as platinum and nichrome, when heated above 500-600°C, give off positive ions and few negative ions (18,22). Both positive and negative ions are emitted only when the metal reaches a temperature of approximately 1000°C.

The positive equivalent current increase due to the presence of a positive ion generator, as shown in Figure 29,
is self-explanatory. The slight decrease in the negative equivalent current is probably due to the decrease in the negative ambient ionization caused by the increased recombination with the abundant positive ions.

A kerosene lamp might be expected to give a larger increase than observed. However, ions may be lost to the metal housing surrounding the wick. Furthermore, it was difficult to adjust the flame without having a great amount of smoke and carbon particles present. These particles would absorb the majority of the small ions, becoming large ions in the process. Such large ions have a very low mobility and perhaps would not be affected by the weak electric fields. Perhaps few ions are produced when kerosene is burnt since a naptha gas lantern gave a large increase in the positive charge accumulation rate as shown in Figure 24.

The large increases in the positive and negative equivalent currents for the operation of a tesla coil, as shown in Figure 36, indicate that abundant ionization occurred. This was the result when the discharge took place between the coil and a grounded metal conductor. Only small increases were observed for discharge to a non-grounded conductor. A much higher rate of recombination would probably explain this last observation.
Relative Humidity

The small changes in the equivalent currents caused by varying conditions of relative humidity did not show any distinction between ionization of each polarity. It might be expected that negative ionization would increase because of the Lenard effect. However, the large negative ions, if produced, might not be detected by the weak fields. Furthermore, combination and recombination rates would be expected to increase with higher levels of relative humidity.

Uni-Polar Ion Sources

The hair dryer, hot plate, toaster and radiant heater produced predominantly positive ions. The naptha gas lantern also produced abundant positive ions and few negative ions.

It is noted that the system will not detect these ion sources if the high voltage grid has a positive polarity. The positive ions are repelled to ground under this condition. Only when the high voltage grid is negative will these ions accumulate on it and subsequently be measured by the electrometer system.

A fire detection system based on the charge accumulation principle is best suited for night-time protection of residences and industries. Under these conditions, disturbing factors (such as hot plates, tesla coils, gas lanterns, etc.)
would not be present and the system would alarm only with the presence of flame.

3.5 Design of a Prototype System

3.5.1 Description of the System Grid

A prototype model was built and tested in the Environmental Test Chamber, a 2m x 4m x 2m unshielded wooden structure, also located in the Electrostatics Research Laboratory. A 1.2m x 3m rectangular loop of teflon insulated high voltage cable was attached to the ceiling by teflon supports. Two power supplies, an electrometer, a program timer, an alarm and connecting circuitry formed an automatic detecting device. The system is shown in Figures 41 and 42.

Timing and Switching

Charge accumulation measurements and voltage polarity switchings were done in synchronism by using a Cramer Model 540 Multiple Pole Program Cycling Timer as shown in Figure 43.

A Cramer high-torque single strength synchronous motor drives this unit. A gear on the motor output shaft drives the timer camshaft, through a replaceable gear-change arm, to provide the desired cycle speed, which was 0.25 rpm.

The main camshaft was furnished split just forward of the first cam from the motor. A 12:1 reduction gear ratio allowed the second cam to cycle at 3 rpm.
FIGURE 41: PHOTOGRAPH OF PROTOTYPE SYSTEM
The camshaft gear is attached to the camshaft by a friction clutch, permitting manual rotation of the camshaft while the motor shaft remains stationary. The split design, switch actuating cams are adjustable by means of a knob and dial. Adjustment of the ON/OFF points of the load circuit from 2-98% of the full cycle period is possible.

The cams operate SPDT snap-acting load switches rated at 10 amps, 115 volts resistive load.

The slow cycling cam switched the voltage polarity while the electrometer was switched by the faster cam. The switching sequence is shown in Figure 44. The voltage polarity was switched every 2 minutes while the electrometer had a 20 second cycle period (10 seconds on, 10 seconds off). A high degree of sensitivity was assured by using the 2 minute time interval between polarity switching.
Alarm

The Keithley Instruments Model 602 Electrometer used had a ±1 mA output for a full scale deflection on any range. This output was used to trigger the alarm system shown in Figure 45.

The sensitivity of the charge accumulation measurements was set a range lower than that required for full scale ambient readings. With this sensitivity and the meter switch at center zero, an audible alarm resulted whenever full scale deflection of either polarity was obtained.

Testing

The prototype was tested under ambient and different combustion source conditions. The fire tests were conducted using paper, oil, wood, and gasoline as the combustibles.

Fire tests were conducted by igniting the combustibles in a metal waste paper basket, located on the floor in the middle of the room. For comparison purposes, a standard bimetallic switch thermostat, rated at 135°F, was mounted on the middle of the ceiling, directly above the combustion source. This thermostat formed the sensor of a standard fire alarm operating in the heat stage of the fire (EICO Kit No. EC-102).
$C_1$ - 0.47$\mu$F CAPACITOR

$K_1$ - 1 VOLT SPDT RELAY, 1000 OHM COIL

$R_1$ - 1000 OHM, 1/2 WATT RESISTOR

$R_2$ - 50 KILOHM POTENTIOMETER

$R_3$ - 100 OHM, 1/2 WATT RESISTOR

$Q_1$ - 2N170 TRANSISTOR

$Q_2$ - 2N107 TRANSISTOR

$B_1$ - 1.5 VOLT BATTERY

$SPKR$ - 3 OHM SPEAKER

FIGURE 45: CIRCUIT DIAGRAM OF ALARM
Electric Field

An electric field plot, shown in Figure 46, indicates that the electric field strength is fairly uniform and approximately equal to 400 volt/meter for an applied voltage of 1000 V. For testing purposes, two 500 volt power supplies were used in conjunction with two high voltage relays to give fields of approximately ±200 volt/meter.

Grid to Ground Capacitance

Using the method of images, as shown in Appendix II, the grid to ground capacitance was found to have an approximate value of $32.9 \times 10^{-12}$ farad.

3.5.2 Operating Results

Ambient readings were taken and a typical set of results is shown in Figure 47.

The meter range was set an order of magnitude higher for the fire tests. The results of four fire tests conducted are given in Table 5.
FIGURE 46: ELECTRIC FIELD PLOT OF PROTOTYPE GRID SYSTEM
FIGURE 47: RATE OF CHARGE ACCUMULATION VS. TIME FOR PROTOTYPE SYSTEM, AMBIENT CONDITIONS
<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>COMBUSTIBLES</th>
<th>PEAK ACCUMULATED CHARGE IN 10 SEC. $\times 10^{-8}$ C.</th>
<th>PROTOTYPE RESPONSE TIME (SEC.)</th>
<th>HEAT DETECTOR RESPONSE TIME (SEC.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wood Paper</td>
<td>5</td>
<td>10</td>
<td>Did Not Respond</td>
</tr>
<tr>
<td>2</td>
<td>Paper Cloth</td>
<td>6</td>
<td>13</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Gasoline Paper</td>
<td>4.5</td>
<td>8</td>
<td>Did Not Respond</td>
</tr>
<tr>
<td>4</td>
<td>Paper Oil</td>
<td>6</td>
<td>18</td>
<td>45</td>
</tr>
</tbody>
</table>

**TABLE 5: RESULTS OF PROTOTYPE FIRE TESTS**
3.5.3 Possible Uses as a Burglar Alarm System

An interesting point to consider is the response of the system to the change in capacitance caused by a person entering the room. The presence of a person increases the capacitance between the grid and ground. Tests showed that an alarm resulted when a person entered the room while charge was being measured on the $10^{-9}$ coulomb scale. However, the system was also found to alarm on each polarity switching when charge was being measured at this level. This was the result of the large initial charge accumulation rate caused by the repulsion of charge from the insulated grid.
CHAPTER FOUR

CONCLUSIONS

A. From the results of the model fire test chamber experiments, the following conclusions can be drawn with respect to the effectiveness of this fire detection system.

1. The magnitude of the rate of charge accumulation, both for ambient and combustion conditions, is dependent on the voltage applied between the upper grid and ground. The electric field created by this potential difference reduces the recombination of the ions and therefore increases the number collected.

2. The build-up of accumulated charge on the grid insulation necessitates voltage polarity switching to make the system sensitive at all times. Without polarity switching, the accumulated charge effectively reduces the electric field between the collecting grid and ground, thereby reducing the collecting efficiency of the system.

3. The system did not detect the presence of, a vaporizer, a vacuum cleaner, a sunlamp and a circulating air fan.
4. Small increases in the rate of charge accumulation, (1-5 times the ambient), were observed with the presence of a hair dryer, a toaster, a radiant heater, a positive ion generator, an electric kettle, a kerosene lamp, cigarette smoke, and high relative humidity conditions.

5. Moderate increases in the rate of charge accumulation, (5-20 times the ambient), were observed with the presence of a naptha gas lantern, a 1500 watt hot plate and with 1 or 2 candles.

6. Large increases in the rate of charge accumulation, (20-200 times the ambient), were observed for the combustion of cloth, wood, "Kimwipes", paper, an air-propane flame, 2-12 candles, and for the operation of a tesla coil.

B. From the results of fire tests conducted with the prototype model, the following conclusions are to be noted.

1. The system had a response time of 10 seconds for the detection of a paper-wood fire.

2. The response time was 13 seconds for the detection of a paper-cloth fire.

3. The system responded in 8 seconds to a gasoline-paper fire.
4. The response time was 18 seconds for a paper-oil fire.

5. In all tests, the prototype system had a faster response time than a heat sensitive detector.

6. The system will effectively detect the entrance of a person into the protected volume when the electrometer is set on a more sensitive scale, than is used for fire detection.

C. The system will detect a fire in its flame stage. Conditions which produced small or moderate changes in the ionization detected in the fire test chamber apparatus gave negligible increases in the prototype system experiments because their influence is proportionally scaled down in the larger system. Fire detection is most effective at night when disturbing factors (such as hot plates, tesla coils, etc.) are not present.

The system may be adjusted to function as a burglar alarm.
CHAPTER FIVE

RECOMMENDATIONS FOR FUTURE STUDY

It would be interesting and useful to perform a series of experiments in which a relationship between ion recombination rates in an electric field and the strength of the electric field could be obtained. These experiments would require the use of an ion counter to monitor ion concentration levels. Such a study would enable quantitative evaluation of the qualitative results obtained in this project.

Since it is desirous to make a fire detection system as maintenance free as possible, a further investigation of the components of this system is necessary. A completely solid state device would eliminate any moving parts and extend the life and reliability of the system. In addition, it is necessary to design a low-cost power supply to meet high voltage, low current requirements.

An investigation of the charges collected in the first few seconds immediately after the voltage polarity switching is needed. It may be possible to devise equipment to perform the charge integration directly after the voltage is switched. A gain in sensitivity would be expected.
APPENDIX 1

Variation in Electric Fields

Substitution of the following values for the parameters of the system, yields numerical approximations for the electric fields, $E_1$ and $E_2$.

$$d_1 = 22.86 \times 10^{-4} \text{ meter}$$

$$d_2 = 0.61 \text{ meter}$$

$$V = 1000 \text{ volt}$$

$$\varepsilon = 2.1 \text{ (Teflon)}$$

$$\varepsilon_0 = 8.85 \times 10^{-12} \text{ farad/meter}$$

$$P_s = 0 \text{ (assume an ideal dielectric)}$$

Initially, assume $\sigma_r = 0$; there is initially no surface charge on the insulation.

Then,

$$E_1 = 780 \text{ volt/meter}$$

and $$E_2 = 1640 \text{ volt/meter}$$

120
As the charge accumulates on the insulation of the high voltage cable, \( E_1 \) increases rapidly and \( E_2 \) decreases slowly.

Sample Calculation

Since \( \varepsilon_0 Kd_2 \gg \varepsilon_0 d_1 \),

\[
E_1 = \frac{V}{Kd_2 + \frac{\sigma_r}{\varepsilon_0 K}}
\]

\[
= (780 + 5.4 \times 10^{10} \sigma_r) \text{ volt/meter}
\]

\[
E_2 = \frac{V}{d_2} - \frac{\sigma_r d_1}{\varepsilon_0 Kd_2}
\]

\[
= (1640 - 2.02 \times 10^8 \sigma_r) \text{ volt/meter}
\]

Consider a protected volume of 10m\(^3\).

Estimate the average ambient concentration of small ions at 1000 ions/cm\(^3\) = 10\(^9\) ions/m\(^3\).

With a length of cable = 4 meter, the surface area of the insulation = \( \pi \times 57.12 \times 10^{-4} \times 4 = 0.11m^2 \).

The mobility of the small ions is approximately 1 cm\(^2\)/volt sec = 10\(^{-4}\) m\(^2\)/volt sec.

Assuming an initial field of 1640 volt/meter, the velocity of the small ions will be .164 meter/sec.
After 10 seconds, the ions in the protected volume, approximately $10^{10}$, will have accumulated on the initially charge-free surface of the insulated conductor.

Surface charge density at the end of 10 seconds

$$\frac{10^{10} \times 1.6 \times 10^{-19}}{0.11} = 1.45 \times 10^{-8} \text{ coulomb/m}^2.$$ 

At the end of 10 seconds,

$$E_1 = 780 + 783 = 1463 \text{ volt/meter}$$

$$E_2 = 1640 - 3 = 1637 \text{ volt/meter}$$

The same result can be obtained by an alternate calculation. By interpolation to time $t = 0$ in Figures 5 and 6, an approximate value for the equivalent current immediately after switching is $1 \times 10^{-10} \text{A}$.

This is equal to \( \frac{1 \times 10^{-10}}{1.6 \times 10^{-19}} = 0.625 \times 10^{19} \text{ ions/sec} \).

With a length of cable $\approx 4\text{m}$, with a diameter of $50 \times 10^{-4}\text{m}$, the surface area of the insulation is

$$\pi \times 50 \times 4 \times 10^{-4} = 0.063\text{m}^2.$$ 

After 10 seconds, approximately $10^{10}$ ions will have accumulated on the initially charge-free insulated surface of the conductor.
Assuming the charge is uniformly distributed, the surface charge density at the end of 10 seconds is

$$\sigma_r = \frac{10^{10} \times 1.6 \times 10^{-19}}{0.063} = 2.54 \times 10^{-8} \text{ coulomb/m}^2.$$

At the end of 10 seconds,

$$E_1 \approx 780 + 1370 = 2150 \text{ V/m}$$

$$E_2 \approx 1640 - 5.1 = 1634.9 \text{ V/m}.$$
One Insulated Cylindrical Conductor Above Ground

Consider an infinite cylinder of radius $a$ at a distance $d_2$ above an infinite conducting plane as shown in Figure 48.

The following assumptions will be made.

i) The insulated conductor is represented by a perfectly cylindrical geometry.

ii) A uniform charge distribution exists on the surface of the insulation.

iii) The insulation resistance is $\infty$.

Gauss' theorem is applied. If a cylindrical Gaussian surface is considered to enclose the insulated conductor, the total electric flux leaving the surface will equal the total enclosed charge divided by $\varepsilon_0$. Thus, if the conductor is at a positive potential with respect to ground, the negative charge accumulating on the insulation of the conductor will result in a reduction of the electric field intensity, $E_0$. 

124
FIGURE 48: INFINITE CYLINDRICAL CONDUCTOR ABOVE AN INFINITE CONDUCTING PLANE
A potential of 1000 volts is applied between this conductor and ground. This establishes a positive charge on the wire per unit length of $\lambda$ coulomb/m. It is necessary to calculate the capacitance of the conductor to ground, $C_{gg}$, before $\lambda$ can be determined. Having calculated the initial electric field intensity between the conductor and ground, its variation as the result of accumulated charge can be determined.

The values of the parameters to be used are

\[
d_2 = 0.6\text{m}
\]
\[
a = 5.0 \times 10^{-4}\text{m}
\]
\[
r_g = 28 \times 10^{-4}\text{m}.
\]

The capacitance of the conductor to ground is given as follows (48).

\[
C_{gg} = \frac{2\pi \varepsilon_0}{2d_2} \ln\left(\frac{2d_2}{a}\right)
\]

\[
= 7.0 \text{ pf/m}.
\]

For an applied voltage of 1000 volts, the initial positive charge on the conductor is

\[
\lambda = C_{gg} V
\]

\[
= 7.0 \times 10^{-9} \text{ coulomb/m}.
\]
The electric field produced at any point \( P \), displaced \( s \) metres horizontally and \( y \) metres vertically downward as shown in Figure 48, can be calculated (48).

\[
E_0 = -\frac{\lambda y}{a y \pi \varepsilon_0 (y^2 + s^2)}
\]

Considering the electric field directly below the conductor, i.e. \( s = 0 \), the expression becomes

\[
E_0 = -\frac{\lambda}{\pi \varepsilon_0 y}.
\]

For the initial value of \( \lambda \),

\[
E_0 = -\frac{a y}{252}.
\]

From Figures 5 and 6, it is estimated that, in the first 2-3 minutes after polarity switching, approximately \( 5 \times 10^{-11} \) coulomb/sec of negative charge is accumulated on the 4 metre grid.

Since the accumulated charge is negative, the net positive charge on the conductor is decreased which results in a decrease of the initial electric field \( E_0 \) to a new value \( E_2 \).
Sample Calculation

At the insulated conductor surface, 
\[ y = r_g = 28 \times 10^{-4} \text{ m}. \]

Initially,

\[ E_0 = \frac{2 \pi r_g^2}{2 \pi r_g^2} = 9.0 \times 10^4 \text{ V/m}. \]

After 1 minute, approximately \( 0.75 \times 10^{-9} \) coulomb/m of negative charge will have accumulated. This reduces the electric field to

\[ E_2 = \frac{(7.0 - 0.75) \times 10^{-9}}{\pi \varepsilon_0 \times 28 \times 10^{-4}} \]

\[ = 8.35 \times 10^4 \text{ V/m}. \]

After 10 minutes, the initial value of \( E_0 \) will be reduced to zero.

Figure 49 shows the variation of \( E_2 \) with time for various points between the conductor and ground.
FIGURE 49: ELECTRIC FIELD AS A FUNCTION OF TIME FOR VARIOUS DISTANCES FROM A CONDUCTOR ABOVE GROUND
APPENDIX 3

Grid to Ground Capacitance

Consider two parallel wires stretched above the earth as shown in Figure 50.

The parameters of the system as shown, have magnitudes as follows.

\[ a = 5.7 \times 10^{-4} \text{ m.} \]
\[ r_1 = 1.22 \text{ m.} \]
\[ r_2 = 4.15 \text{ m.} \]
\[ r_3 = r_4 = 3.96 \text{ m.} \]

Employing images, the capacitances of the system can be calculated (48).

\[
C_{11} = 2\pi \varepsilon_0 \frac{\ln \frac{r_1}{a} \frac{r_4}{r_2}}{\ln \frac{r_3}{a} \ln \frac{r_4}{a} - \ln^2 \frac{r_2}{r_1}}
\]

\[
C_{22} = 2\pi \varepsilon_0 \frac{\ln \frac{r_1}{a} \frac{r_3}{r_2}}{\ln \frac{r_3}{a} \ln \frac{r_4}{a} - \ln^2 \frac{r_2}{r_1}}
\]
FIGURE 50: SYSTEM OF TWO PARALLEL WIRES
ABOVE GROUND
\[ C_{12} = 2\pi\varepsilon_0 \left( \ln \frac{r_2}{r_1} \right) / \ln \frac{r_3}{r_1} \ln \frac{r_4}{\alpha} - \ln^2 \frac{r_2}{r_1} \]

All capacitances are expressed in farads/meter.

Substitution yields the following capacitance values.

\[ C_{11} = C_{22} = 5.4 \times 10^{-12} \text{ f/m} \]

\[ C_{12} = 6.5 \times 10^{-12} \text{ f/m} \]

The approximate total capacitance to ground is therefore \(10.8 \times 10^{-12} \text{ f/m}\).

Since the length considered was approximately 3 m, the total capacitance of the system is approximately \(32.4 \times 10^{-12} \text{ f}\).
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