THERMIONIC IONS GENERATED IN NITROGEN
AND CARBON DIOXIDE

by

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SIGNED:

[Signature]

Frederick W. Shaver
ACKNOWLEDGMENT

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F. W. S.
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The problem is to determine the behavior of positive and negative ions produced by thermionic means in nitrogen and carbon dioxide at atmospheric pressure. It is treated by generating the ions in the gases in the presence of an applied electric field and measuring the magnitudes of the ion currents produced. The mobility can be determined as a function of this current and the applied voltage.

This chapter gives a brief summary of existing equations for the emission of both electrons and positive ions from hot metals. There is a discussion on the formation of both positive and negative ions in a gas. The mobility of an ion moving under the influence of an electric field is defined and discussed briefly. Two processes of deionization are also discussed.

1.1 THERMIonic EMISSION OF ELECTRONS

The most widely accepted equation for the emission of electrons from a clean pure metal with zero field at the
emitter is Dushman's equation which states that

\[ J = A_o T^2 e^{-b_o/T} \]  \hspace{1cm} (1.1)

where \( J \) = current density in amps per square meter of cathode area,
\( T \) = temperature of the cathode in degrees Kelvin,
\( b_o = eE_w/K = 11,600E_w \),
\( E_w \) = work function of the metal,
\( e \) = electronic charge,
\( K \) = Boltzmann's constant,
\( A_o = 4\pi meK^2/h^2 \) = proportionality constant in amps per meter\(^2\) per degree\(^2\),
\( h \) = Planck's constant,
\( m \) = electron mass.

Theoretically \( A_o \) should be a universal constant having a value of \( 120.4 \times 10^4 \) amp/meter\(^2\)/degree\(^2\) for the emission of electrons. This has not been verified experimentally however, and in the case of several metals the value has been determined experimentally to be \( 60.2 \times 10^4 \) amps/meter\(^2\)/degree\(^2\), just half of the theoretical value. The reason for this is not known.

To find \( A_o \) and \( b_o \) experimentally the emission equation is put in the form

\[ \log_{10} J/T^2 = \log_{10} A_o - 0.4343b_o/T. \] \hspace{1cm} (1.2)

If the left hand side of the equation is plotted against \( 1/T \), the result should be a straight line with an intercept of \( \log_{10} A_o \) and a slope of \(-0.4343b_o\). This method of
determining the constants is not too accurate because of limited temperature ranges, surface impurities, and difficulties involved in the measurement of temperature.\(^1\)

When the electric field at the emitting surface becomes greater than zero, the electrons being emitted are acted upon by the field. This is the Schottky effect. Under these conditions the emission current density from a pure metal is given by

\[
J = J_0 \varepsilon 3eE^{1/2}/2kT
\]  

(1.3)

where \(J = \) current density with the field present,

\(J_0 = \) current density with no field present,

\(E = \) electric field intensity at the emitter surface.

This equation is derived using the assumption that the electric field causes a lowering of the work function of the metal.\(^2\)

To verify experimentally the equation developed in Chapter 2 of this thesis, it is necessary that the ion current with zero electric field at the emitter be known. To find this current a plot of the form in Figure 1.1 can be made.

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In this plot the plate voltage is held constant, and the plate current is measured as a function of the filament temperature. The condition of zero field at the emitter surface occurs at the point of transition from the temperature limited condition to the space charge limited condition. The current can easily be determined by this method because the space charge region is horizontal, and extrapolation to the current axis gives the desired value.¹

¹T. L. Martin, Jr., and C. R. Hausenbauer, Notes on Thermionic Ion Generation in Gases, for National Science Foundation grant NSF-G767, pp. 1.6–1.7 (citing "Elements of Thermionics," Proceedings of the IRE, May, 1951, p. 486, by N. E. Danforth).
1.2 THERMIonic EMission of Positive Ions

A. von Engel\(^1\) states that when a metal is heated to a sufficiently high temperature, positive ions as well as neutral atoms are evaporated. The ion current density is given by an equation of the form

\[ J^+ = C_1 T^2 e^{-11.600E_{m^+}/T} \quad (1.4) \]

where \(C_1\) is a constant and \(E_{m^+}\) is a work function for positive ions and is larger than the work function for electrons.

Materials present as impurities on the surface of an emitter may be evaporated as positive ions. For this to occur the work function of the surface must exceed the ionization potential of the atom which is to be evaporated as an ion. Sometimes neutral atoms of the vapor surrounding the filament diffuse into the emitter surface where they lose an electron and are repelled as positive ions. It is also possible that positive ions of the pure metal filament are evaporated, but the currents caused in this way are small compared to other emission currents.\(^2\)

Emission of platinum ions from heated platinum is observed only in a rush of current just before the filament burns out. Almost all positive ions from platinum at ordinary temperatures seem to come from alkaline impurities.

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The supply of ions does not seem to diminish to zero even after extensive heating.¹

1.3 FORMATION OF GASEOUS IONS

In discussions concerned with ion formation by collision between electrons and atoms or molecules, mention is made of several different types of impact which can occur. An elastic collision is one in which there is no energy exchanged. In an inelastic collision there is an exchange of energy, and the atom may become ionized or, it may become excited. Another type of collision is the superelastic collision in which an electron colliding with an excited atom gains energy from the atom. This occurs only when the atom has been excited before the collision.²

Collision cross-section is a representation of the possibility of a collision between two particles. In one of the most common approaches to the problem the atoms are considered solid spheres, and the cross-section is the cross-sectional area of these spheres. However, since atoms


²T. L. Martin, Jr., and C. R. Hausenbauer, Notes on Thermionic Ion Generation in Gases, for National Science Foundation grant NSF-G767, p. 4.1 (citing Electronic and Ionic Impact Phenomena, pp. 1-2, by H. S. W. Massey and E. H. S. Burhop).
are not solid spheres, the cross-sectional area depends on the state of the atom and the force of attraction between the nucleus and the electrons.¹

High energy electrons moving in a gas may cause the gas to become ionized by a single collision, but because of the conservation principles involved and the many possible angles of collision there is a greater possibility that ionization will occur by a series of collisions rather than a single one. A collision will usually not be head-on so the angular momentum of the electron and atom (or molecule) with respect to the common center of mass of system has to be conserved. If the energy of the electron is higher than the energy required to just excite the atom, the probability of excitation becomes much greater because the primary electron can carry away the excess energy and also balance the momentum. Excited atoms being bombarded by electrons may eventually lose an electron thus forming positive ions. The energy required to ionize an atom or molecule is known as the ionization potential. A list of ionization potentials is given in Table I.

¹T. L. Martin, Jr., and C. R. Hausenbauer, Notes on Thermionic Ion Generation in Gases, for National Science Foundation grant NSF-G767, pp. 4.3-4.4 (citing Electronic and Ionic Impact Phenomena, p. 2, by H. S. W. Massey and E. H. S. Burhop).
An electron moving toward an atom will deviate from its path because of the forces set up between it and the electrons in the atom. If the forces exerted by the primary electron are sufficiently large and act for a sufficiently long time, a secondary electron may be ejected from the atom. If the energy of the primary electron is extremely high, it may move through the atom without causing any change. If the energy of the primary electron is very small, it may be repelled by the atomic electrons and cause no change in the atom except perhaps a certain degree of polarization. Since the energy of the primary electron may be too large or too small to cause any change, it is seen that there is an optimum energy which a primary

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An electron can have to cause ionization.¹

Ionization by molecular ions and atoms of low energy is not too probable because of the large mass and low relative speed. These particles spend a comparatively long time in the neighborhood of other atoms, so there is a good chance the electrons adjust their positions but remain in the atom while momentum is exchanged. Since the time of contact is so long in this case, it is possible that there is a transfer of charge from an electron to an ion, thus making the ion a neutral atom and the atom a positive ion. Thus an ion is not formed by collision, but one is formed by charge transfer.² Cobine³ makes the following statement in speaking of positive ions: "Ions apparently begin to be effective ionizers when their velocities are as great as those of electrons which have fallen through the minimum ionization potential. In this case the kinetic energy of the ions is of the order of thousands of volts, and they become even more effective ionizers than the electrons."⁴

At the electrodes several processes of secondary emission may occur. If an electron falls on a metal surface and has an energy greater than the work function of

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³Cobine, op. cit., p. 84.
the surface, a secondary electron may be emitted. There is also a secondary emission effect caused by positive ions impinging on the surface of the metal. Here, both charged and uncharged particles are emitted. The charged particles are usually slow secondary electrons from the metal, or in rare cases they may be reflected positive ions. The uncharged particles are often molecules of the gas which were in contact with the surface or neutralized positive ions returning to the gas. When atoms of a gas of ionization potential $V_i$ fall on a surface which has a work function $E_w$, electrons will be removed from the atoms if $E_w > V_i$.  

For photoionization to occur, "$hf$" of the photon must be greater than "$eV_i$" of ionization. $h$ is Planck's constant, $f$ is the frequency of the wave in cycles/second, $e$ is electronic charge, and $V_i$ is the ionization potential. The number of ions produced by this process is believed to be small compared to the number produced by the other means mentioned.  

Ions as well as atoms may be regarded as systems with a number of quantum states. In the normal state the energy of an atom is $E_o$, and the energy of an ion is $E_-$. If a

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stable negative ion is formed \( E_0 - E_+ > 0 \). \( E_0 - E_+ \) is the electron affinity of the atom. The electron affinity of nitrogen is 0.04 electron volts which is very small compared with that of other elements. For example, oxygen has an electron affinity of 3.8 electron volts. This low value of electron affinity for nitrogen means that the formation of a negative nitrogen ion is very uncommon.¹

When electrons or positive ions move under the influence of an electric field in a gas that does not easily form negative ions, they may, by collision, produce more positive ions and free electrons. The energy given to the particles by the electric field increases the probability that this will happen. Therefore, a primary electron starting at the negative electrode may be multiplied several times before it reaches the anode.²

1.4 MOBILITY

The mobility of an ion is the component of velocity in the direction of the electric field when a unit electric field is applied.³ In other words the drift velocity of

¹T. L. Martin, Jr., and C. R. Hausenbauer, Notes on Thermionic Ion Generation in Gases, for National Science Foundation grant NSF-G767, pp. 416-417 (citing Negative Ions, p. 3, by H. S. W. Massey).


³Ibid., p. 94.
the ions is \( v_d = kE \) where \( k \) is the mobility and \( E \) is the electric field intensity. Solving this for \( k \) yields

\[
  k = \frac{v_d}{E}. \tag{1.5}
\]

If a weak electric field (so there is no excitation and ionization) is applied to ions moving in their own gas, the path followed by an ion will be irregular as shown in Figure (1.2).

![Figure (1.2)](image)

In treating a single ion in this manner, it is assumed that the interaction between this and other ions can be neglected. It is also assumed that the ions are in thermal equilibrium with the gas and after a collision the velocity of an ion is the same as if the ion were a neutral gas molecule. The electric field tends to pull the ion toward one of the electrodes. After the ion moves along a path whose average length is equal to a mean free path, it will collide with another molecule and rebound at random, but the ion will always on the average proceed in the direction dictated by the field. During the period between collisions the ion moves as if it were in a vacuum,
and its acceleration is \( a = \frac{eE}{M} \) where \( e \) is the charge and \( M \) is the mass of the ion.

If \( \lambda_i \) is the ionic mean free path and \( v_i \) is the mean velocity of the ion, the time between collisions is \( t = \frac{\lambda_i}{v_i} \).

If the time of actual impact is neglected the distance traveled by the ion is \( s = \frac{1}{2}at^2 = \frac{(eE/2M)t^2}{2} \). The drift velocity is \( v_d = \frac{eE}{2M}t = \frac{(e\lambda_i/2Mc)}{E} \).

From equation (1.5) \( v_d = kE \), therefore it would appear that \( k = (e\lambda_i/2Mc) \).

However, von Engel\(^1\) makes the following statement: "Because of the statistical distribution of mean free path, \( k \), the mobility, is apparently twice as large, namely

\[
k \approx \frac{e\lambda_i}{Mc}.
\]

From equation (1.6) it appears that there would be an undetectable difference in the mobilities of singly charged positive and negative ions, because there is only a very little difference in mass. If the equation is applied to electrons, however, the mobility would be increased by a factor 1,870 times the molecular weight of the gas. "Observations show that there is no difference between the mobility of positive and negative ions of the same gas unless the negative ion exists for a certain fraction of its life as a free electron."\(^2\)


\(^{2}\)Ibid.
In air the mobility of negative ions is slightly larger than the mobility of positive ions because oxygen molecules have a great affinity for a free electron. The formation of negative nitrogen ions, on the other hand, is a rare process, and mobility measurements in pure nitrogen yield values up to 20,000 cm/sec per volt/cm indicating that the ions are free electrons. In air it seems that a majority of the electrons become attached to oxygen molecules, but a few remain as free electrons and cause an increased average mobility.

In some instances the measured values of mobility of positive ions have been 3 to 5 times smaller than the values obtained from equation (1.6). This is explained by assuming the formation of clusters. When clusters are formed the mass is not that of a single molecule but that of the ion and several impurity molecules surrounding it. The effective diameter of the ion is also increased, so the mean free path will be decreased.¹

Langewin and J. J. Thomson developed a theory of ionic mobility which took into account the dipole nature of a gas. In this theory the ion induces temporarily an electric dipole moment in neighboring molecules as it moves through the gas. The force of attraction between the ion

and the dipoles cause the ion to be deflected from the
direction it is caused to move by the electric field. An
exchange of momentum between the ion and the gas molecule
will occur even though there is no actual collision. It
has been found that the degree of polarization increases
with atomic number.

The result of this treatment is an equation of the
form

\[ k = A \left( \frac{1 + \frac{M}{M_1}}{\delta(D - 1)} \right)^{1/2} \]  \hspace{1cm} (1.7)

where \( M \) and \( M_1 \) are the masses of the molecule and ion, respec-
tively; \( A \) is a constant dependent on \( D \), on the sum of
the radii of the ion and the molecule, and on the gas tem-
perature; \( D \) is the dielectric constant; and \( \delta \) is the gas
density. Experimental results have been obtained which
confirm this equation fairly well, and measurements using
ions of the alkalis in rare gases and nitrogen have shown
the dependence of \( k \) on \( M/M_1 \). ¹

A fast moving positive ion colliding with a molecule
 can result in the ion extracting an electron from the mole-
cule. This results in a fast ion becoming a fast molecule
and a slow molecule becoming a slow positive ion. This
charge transfer causes a reduction in the effective drift
speed of the ion, and hence the mobility seems to be

Mobility is determined by four factors: (1) the size of the ion, (2) polarizability of the gas, (3) charge transfer, and (4) the pressure of the gas. Table II gives a list of the most probable values of mobility.

It has been found from experiment that the mobility of an ion is constant only over a particular range of values of the ratio of the electric field intensity to the gas pressure. When values of this ratio are large, the mobility becomes variable. In Chapter 2 it will be shown that the ratio in the experiment is about 0.3 to 1.0 volts/meter per millimeter of mercury. Mobility seems to be a constant in this range.

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Table II

The Most Probable Values of Mobilities of Singly Charged Gaseous Ions at 0°C and 760 mm Hg,\(^1\)
(in units of \(10^{-4}\) m/sec per volt/m)

<table>
<thead>
<tr>
<th>Gas</th>
<th>(k^-)</th>
<th>(k^+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air dry</td>
<td>2.1</td>
<td>1.36</td>
</tr>
<tr>
<td>Air very pure</td>
<td>2.5</td>
<td>1.8</td>
</tr>
<tr>
<td>CO</td>
<td>1.14</td>
<td>1.10</td>
</tr>
<tr>
<td>CO(_2) dry</td>
<td>0.98</td>
<td>0.84</td>
</tr>
<tr>
<td>H(_2)</td>
<td>8.15</td>
<td>5.9</td>
</tr>
<tr>
<td>He</td>
<td>6.3</td>
<td>5.09</td>
</tr>
<tr>
<td>He very pure</td>
<td>500</td>
<td>5.09</td>
</tr>
<tr>
<td>N(_2)</td>
<td>1.84</td>
<td>1.27</td>
</tr>
<tr>
<td>N(_2) very pure</td>
<td>145</td>
<td>1.28</td>
</tr>
<tr>
<td>N(_2)O</td>
<td>0.90</td>
<td>0.82</td>
</tr>
<tr>
<td>O(_2)</td>
<td>1.8</td>
<td>1.31</td>
</tr>
</tbody>
</table>

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1.5 DEIONIZATION IN A GAS

One deionizing process that takes place in a gas is caused by diffusion. That is, the ions move from areas of high concentration to areas of low concentration. Much of this movement is caused by the mutual repulsion set up between two ions of the same sign. If the ions diffuse in the same direction as the electric field acting on them, their velocity will be the sum of the velocity due to the diffusion process and the velocity caused by the electric field. Since the mobility of the ions is directly proportional to the velocity, this will result in an increased mobility.¹

Another deionizing process is the recombination of two ions of opposite sign. If two oppositely charged ions should happen to come near one another, there is a force of attraction set up between them. The negative ion will lose its loosely bound electron to the positive ion, and both will become neutral atoms or molecules. The energy evolved by the recombination of slow ions is approximately the same amount that was required to produce the ions from neutral molecules. This energy can appear as an increase of kinetic energy of the two molecules, as excitation energy, or as radiation emitted during the actual recombination.

period. Because linear momentum, angular momentum, and spin must be conserved, the increase in kinetic energy is probably a rare process. At higher pressures recombination of ions is controlled by the electric field set up by the charges on the ions. The probability of recombination depends on the relative speed of the particles and decreases as the relative speed increases because the time which the particles are close together decreases with increasing speed. If, however, the ion is excited, its effective diameter is greater, and the probability of recombination is greater.\(^1\)

It is possible that the process of deionization may occur in steps. An ion may capture an electron and become an excited molecule. The capture of the electron causes the release of a certain amount of energy. The electron may then move to a lower energy state and release more energy.\(^2\)


\(^2\)Ibid., p. 140.
Chapter 2
HIGH PRESSURE SPACE CHARGE

The high pressure space charge equation derived in this chapter is developed from two derivations; one by von Engel\(^1\) and the other by Martin\(^2\). The result is the same as that obtained by Martin. The remainder of the material in the chapter was taken from Report Number 1, "Thermionic Ion Generation in Contaminated Air and Other Gases."\(^3\)

The author claims no originality in any of these derivations.

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\(^3\) T. L. Martin, Jr., and C. R. Hausenbauer, "Thermionic Ion Generation in Contaminated Air and Other Gases," Report No. 1 Grant NSF-G767, Electrical Engineering Department, University of Arizona, Tucson, Arizona; April 26, 1955, pp. 11, 15.
2.1 DERIVATION OF THE HIGH PRESSURE SPACE CHARGE EQUATION

At high pressure the current density caused by ions moving in a gas is

\[ j = pv_d \]  \hspace{1cm} (2.1)

where \( p \) is the space charge density and \( v_d \) is the drift velocity of the charged particles. In Chapter 1 the drift velocity was given by \( v_d = kE \) where \( k \) is the mobility of the ion and \( E \) is the electric field intensity. Mobility is assumed to be constant. Substituting for \( v_d \) in (2.1)

\[ j = pkE. \]  \hspace{1cm} (2.2)

The current at any point \( r \) in the interelectrode space is given by

\[ I_b = 2\pi rjL \]  \hspace{1cm} (2.3)

where \( L \) is the length of the cylindrical electrodes shown in Figure (2.1). Substituting (2.2) into (2.3) yields

\[ I_b = 2\pi rLpkE. \]  \hspace{1cm} (2.4)
Poisson's equation says
\[ \nabla^2 V = -\frac{p}{\varepsilon} \]
\( \varepsilon \) being the dielectric constant of the medium. If cylindrical coordinates are used, if there is radial symmetry, and if it is assumed that there is no variation of \( V \) in the \( z \) direction this becomes
\[ \nabla^2 V = \frac{1}{r} \frac{d}{dr}(r \frac{dV}{dr}) \]
If the above assumptions are true \( \frac{dV}{dr} = -E \), therefore,
\[ \nabla^2 V = \frac{1}{r} \frac{d}{dr}(rE) = -\frac{p}{\varepsilon} \] (2.5)
From Equation (2.4) \( p = \frac{I_b}{2\pi kE} \). Substituting this into (2.5) yields
\[ \frac{1}{r} \frac{d}{dr}(rE) = \frac{I_b}{2\pi kE \varepsilon} \]
Rearranging terms
\[ rEd(rE) = \left( \frac{I_b}{2\pi kD} \right) rdr. \] (2.6)
In order to solve this equation a boundary condition must be known. The condition that at \( r = a \), \( E = 0 \) will be imposed. Integrating (2.6)
\[ \int_0^E rEd(rE) = \int_a^r \left( \frac{I_b}{2\pi kD} \right) rdr. \]
\( E \) is the electric field intensity at any point \( r \).
Carrying out the indicated integration and solving for the electric field intensity yields
\[ E = \left( \frac{C}{r} \right) \sqrt{r^2 - a^2} \] (2.7)
in which \(C = \sqrt{I_b/2\pi KD}\).

Now \(E = -dV/dr\). Integration of (2.7) gives the inter-electrode potential distribution when the limits of \(E_b\) and 0 at \(r = b\) and \(r = a\) are employed. The eventual result is

\[E_b = -C_bB.\]  \hspace{1cm} (2.8)

where \(B = \sqrt{1 - (a/b)^2} - (a/b) \tan ^{-1} (b/a) \sqrt{1 - (a/b)^2}\).

Squaring (2.8) and substituting for \(C\) gives

\[E_b^2 = \left(I_b/2\pi KD\right)h^2B^2\]

in which \(B\) is a constant determined by the tube dimensions.

Solving for \(I_b\) yields

\[I_b = \left(2\pi KD/h^2B^2\right)E_b^2L.\]  \hspace{1cm} (2.9)

It should be noted at this point that if \(I_b\) is plotted against \(E_b\) on log-log paper, the result should be a straight line with a slope of 2.0.

2.2 FILAMENT DROP CORRECTION

In the tube used there was a drop of approximately five volts along the length of the filament. A correction factor can be derived to compensate for this effect, but this correction will not be complete because of temperature variations along the length of the filament.

Let \(V_z = \) plate-to-filament voltage at any point along the z-axis,

\(V_1 = \) potential at any point on the filament with respect to the grounded end.
The current originating from a differential length of filament is from (2.9):  
\[ dI_b = C_1(E_b \pm V_{fz})^2 dz \]  
where \( C_1 = 2\pi Dk/b^2 B^2 \).

Now if \( V_f \) is the drop across the effective length of filament, and if it is assumed that the filament resistance is constant,  
\[ V_f = V_f(z/L) \]

Then \( dI_b = C_1(E_b \pm V_{fz}/L)^2 dz \)  
\[ = C_1(E_b)^2 \pm 2E_b V_{fz}/L + V_{fz}^2/L^2 dz. \]

Integrating from \( z = 0 \) to \( z = L \) yields  
\[ I_b = C_1E_b^2L(1 \pm V_f/E_b \pm V_{fz}^2/3E_b^2) \]

The filament drop correction is  
\[ C_f = 1 \pm V_f/E_b \pm V_{fz}^2/E_b^2. \]  
(2.12)

Substituting for \( C_1 \) and solving for the mobility yields  
\[ k = (b^2 B^2/2\pi D L)(1/C_f)(I_b/E_b^2).\]  
(2.13)

The following values apply to the diode used:

\[ a = 2.55 \times 10^{-4} \text{ meters} \]
\[ b = 2.70 \times 10^{-2} \text{ meters} \]
\[ L = 7.62 \times 10^{-2} \text{ meters} \]
\[ B = 0.986 \]
\[ D = 10^{-9}/36\pi \]
Substituting these into (2.13) yields:

\[ k = 1.676 \times 10^8 (1/C_F) I_b / E_b^2 \text{ meter/sec per volt/meter}. \quad (2.14) \]

This is the expression for the ion mobility in meters/sec per volt/meter for the diode used in the experiments.

Values of the filament correction factor \( C_F \) for typical operating values of \( E_b \) appear in Table III.

<table>
<thead>
<tr>
<th>( E_b ) (volts)</th>
<th>( C_F(\oplus) )</th>
<th>( C_F(-) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.086</td>
<td>0.924</td>
</tr>
<tr>
<td>80</td>
<td>1.064</td>
<td>0.941</td>
</tr>
<tr>
<td>100</td>
<td>1.051</td>
<td>0.953</td>
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<tr>
<td>120</td>
<td>1.043</td>
<td>0.960</td>
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<tr>
<td>140</td>
<td>1.036</td>
<td>0.966</td>
</tr>
<tr>
<td>160</td>
<td>1.034</td>
<td>0.968</td>
</tr>
<tr>
<td>180</td>
<td>1.028</td>
<td>0.973</td>
</tr>
</tbody>
</table>

2.3 \( E/p \) RATIO OF THE TEST SYSTEM

It has been found that mobility becomes variable when the ratio of electric field intensity to gas pressure is large. The electric field intensity in the interelectrode space can be found by substituting equation (2.9) into equation (2.7). The result is

\[ E = \frac{1}{2} \left[ \frac{E_b}{bb} \left( 1 - \frac{(a/b)^2}{(r/b)^2} \right) \right]^{1/2} \quad (2.15) \]
Substituting numerical values

\[ E = \pm 3.76 \sqrt{1 - \frac{0.899 \times 10^{-4}}{(r/b)^2}} E_b \quad (2.16) \]

From this it is seen that the maximum field intensity will occur when \( r = b \) and when \( E_b \) is a maximum. The maximum value of \( E_b \) used was 180 volts, and the minimum was 60 volts. Using these values \( E \) varies from about 1.0 to 0.3 volts/meter per mm Hg at \( r = b \). These are well below the values of \( E/p \) for which varying mobility has been observed.\(^1\)

\(^1\)T. L. Martin, Jr., and C. R. Hausenbauer, "Thermionic Ion Generation In Contaminated Air and Other Gases," Report No. 1 Grant NSF-G767, Electrical Engineering Department, University of Arizona, Tucson, Arizona; April 26, 1955, p. 15.
Chapter 3

EXPERIMENTAL ASPECTS

This chapter contains a description of the equipment used and the experimental procedure followed in an attempt to experimentally verify the high pressure space charge equation developed in Chapter 2. The experimental results are included and discussed.

3.1 EQUIPMENT USED

The ion currents were produced in a diode configuration which was made up of a cylindrical plate with a concentric filament. The construction of the diode is shown in Figure (3.1). The axis of the tube was placed vertically, and the filament was under a slight tension to prevent bowing. Guard rings were employed at either end of the plate to minimize fringing of the electric field. Cooling plates were placed on the guard rings, plate, and both top and bottom filament supports to help carry away the energy dissipated in heating the filament.

Figure (3.2) shows the essential electrical connections. The filament was heated by a D.C. source, $V_F$. The electric field between the plate and filament was produced by another D.C. voltage supply $E_b$. A Beckman Ulrohmeter was used to measure the ion currents which were of order $10^{-8}$
Approximately 1/2 Size

Figure (3.1)
Reverse the polarity of $E_b$ for negative ion currents.

$V_b$ - Vacuum Tube Voltmeter
$I$ - Ammeter
$I_b$ - Beckman Uitrohmeter
$R$ - Esterline-Angus Graphic Ammeter

---

**Figure (3.2)**

---

1. Diode
2. Bell Jar
3. Compressed Gas
4. Ionization Vacuum Gauge
5. Mechanical Vacuum Gauge
6. Freezing Trap
7. Oil Diffusion Pump
8. Vacuum Pump
9. Pyrometer

**Figure (3.3)**
amperes. An Esterline-Angus Graphic Ammeter was placed in series with the meter on the Ultrahometer when a continuous record of the ion current was desired. An ammeter was used in the filament circuit and a voltmeter was placed across $E_p$ to read the filament current and plate voltage respectively.

Because of the very small currents that were measured, leakage currents had to be kept at a minimum. The bell jar which surrounded the diode was covered with a grounded metal cage. This cage acted as a shield against any stray leakage currents.

In Figure (3.3) the equipment necessary for the control of the atmosphere around the diode is shown. Two types of vacuum pumps were employed to remove the air from the bell jar. One was a rotary, oil-sealed pump, and the other was an oil diffusion pump. A freezing trap was placed between the bell jar and the diffusion pump to freeze any water vapor that might be present in the system. This also served to keep the highly purified oil in the pump from becoming contaminated.

Two gauges were used to measure the amount of vacuum in the bell jar. One was a mechanical vacuum gauge which measured the pressure in inches of mercury, and the other was an ionization gauge which measured the pressure in microns by the glow discharge method of ionizing residual gases in the envelope of the gauge tube.
The gases used in the tests were water pumped nitrogen, prepurified nitrogen, and commercial carbon dioxide obtained from the Matheson Company. Their properties are given in Appendix I.

The Pyrometer shown in Figure (3.3) was used to determine the brightness temperature of the filament.

The filament was number 24 platinum wire. Platinum was chosen because it has a very high melting point, and it does not oxidize.

3.2 EXPERIMENTAL PROCEDURE

The original plan for controlling the atmosphere surrounding the diode was to create a high vacuum in the bell jar and then purge it with the desired gas. The vacuum system used was found to be rather inefficient, so other means of controlling the purity of the gas had to be used. It was discovered (see Appendix II) that the purest atmosphere could be obtained by a series of purgings instead of just one. By doing this the amount of impurity in the gas in the bell jar approached the amount of impurity in the gas itself.

To insure stable operating conditions the filament and all of the measuring instruments were energized for at least one hour before any data was taken. The temperature of the filament during the warm-up period was set in the neighborhood of 1300°C. The range of temperatures between
1300 and 1500°C was found to be most desirable. The upper temperature limit was set just below the breaking temperature of the filament.

The temperature measurements made with the optical pyrometer were not accurate since actually the pyrometer is only good for ideal black body conditions. This is, however, not important because the interest is on the value of ion current when the electric field intensity is zero at the filament surface and not the temperature at which this occurs.

The temperature was varied in approximately twenty degree steps between the two limits. At each filament temperature the plate voltage was varied and the plate current was recorded. The range of plate voltages used was selected so the desired space charge limited condition would exist in the tube over at least part of the temperature range.

If a graphic record of the ion current was desired, the Esterline-Angus Graphic Ammeter was put into the circuit as shown in Figure (3.2).

3.3 EXPERIMENTAL RESULTS

Figure (3.4) shows plate current as a function of filament temperature for negative ions in water pumped nitrogen. Figures (3.5), (3.6), (3.7), (3.8), (3.9), and (3.10) show the ion currents in carbon dioxide. In Figure
(3.4) the current reaches a maximum value and then decreases as the temperature increases, but in the other figures, the current becomes independent of temperature. In all of the figures there is an indication that the tube changes from a temperature limited condition to a space charge limited condition, but the value of current at the transition point cannot be determined for the nitrogen. The ions in carbon dioxide seem to follow more closely the theoretical behavior discussed in Section (1.1).

The maximum values of current from the carbon dioxide tests are tabulated in Table IV. Since the values are so nearly the same for each plate voltage, an average was taken, and this average was plotted against plate voltage on log-log paper in Figure (3.11). These points fall in a straight line which has a slope of 2.0. This agrees with the theory developed in Chapter 2. The average values of current and the mobilities of negative ions in carbon dioxide calculated from equation (2.14) are listed in Table V.
Figure (3.4)

PLATE CURRENT vs. FILAMENT TEMPERATURE

Negative Ions in Nitrogen

PLATE CURRENT (AMPS x 10^-10)

- $E_b=180\,\text{v}$
- $E_b=160\,\text{v}$
- $E_b=140\,\text{v}$
- $E_b=120\,\text{v}$
- $E_b=100\,\text{v}$
- $E_b=80\,\text{v}$
- $E_b=60\,\text{v}$

Temperature range: 1300 to 1500
Figure (3.5)

PLATE CURRENT vs. FILAMENT TEMPERATURE

Negative Ions in Carbon Dioxide

BRIGHTNESS TEMPERATURE (°C)
Figure (3.7)

PLATE CURRENT
vs.
FILAMENT TEMPERATURE

Negative Ions in Carbon Dioxide

PLATE CURRENT (AMPS X 10^-10)

BRIGHTNESS TEMPERATURE (°C)
Figure (3.8)

PLATE CURRENT
vs.
FILAMENT TEMPERATURE

Negative Ions in Carbon Dioxide

PLATE CURRENT (AMPS $\times 10^{-10}$)

BRIGHTNESS TEMPERATURE ($^\circ$C)
PLATE CURRENT vs. FILAMENT TEMPERATURE

Negative Ions in Carbon Dioxide
Figure (3.10)

PLATE CURRENT
vs.
FILAMENT TEMPERATURE

Negative Ions in Carbon Dioxide
### Table IV

Maximum Negative Ion Currents in Carbon Dioxide

<table>
<thead>
<tr>
<th>Figure</th>
<th>E_b (volts)</th>
<th>I_b</th>
<th>I_b</th>
<th>I_b</th>
<th>I_b</th>
<th>I_b</th>
<th>I_b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5</td>
<td>3.6</td>
<td>3.7</td>
<td>3.8</td>
<td>3.9</td>
<td>3.10</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>35</td>
<td>36</td>
<td>--</td>
<td>34</td>
<td>35</td>
<td>33.5</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>62</td>
<td>64</td>
<td>--</td>
<td>60</td>
<td>61</td>
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<td>100</td>
<td>94</td>
<td>94</td>
<td>96</td>
<td>96</td>
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</tr>
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<td>245</td>
<td>250</td>
<td>250</td>
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</tr>
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<td>320</td>
<td>320</td>
<td>320</td>
<td>330</td>
<td></td>
</tr>
</tbody>
</table>

### Table V

Average Negative Ion Currents and Mobilities of Negative Ions in Carbon Dioxide

<table>
<thead>
<tr>
<th>E_b (volts)</th>
<th>I_bAVE</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>34.9</td>
<td>1.76</td>
</tr>
<tr>
<td>80</td>
<td>61.4</td>
<td>1.71</td>
</tr>
<tr>
<td>100</td>
<td>96</td>
<td>1.69</td>
</tr>
<tr>
<td>120</td>
<td>140</td>
<td>1.70</td>
</tr>
<tr>
<td>140</td>
<td>190</td>
<td>1.68</td>
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<tr>
<td>160</td>
<td>254</td>
<td>1.72</td>
</tr>
<tr>
<td>180</td>
<td>323</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Average Mobility = \(1.71 \times 10^{-4}\) meters/sec per volt/meter
Figure (3.11)

PLATE CURRENT vs.
PLATE VOLTAGE

Average Maximum Points

Negative Ions in
Carbon Dioxide

Slope = 2.0
The following three figures - (3.12), (3.13), and (3.14) show the results of three tests made in prepurified nitrogen. The tests in (3.12) and (3.13) were made with the same filament after the bell jar had been purged twice with nitrogen. Here, the magnitudes of the currents are much greater than those obtained in Figure (3.4), but they are approximately the same in these two figures. This is what would be expected since the prepurified nitrogen is more pure than the water pumped nitrogen and since the mobility of negative ions in pure nitrogen is very high (see Section 1.4). The fact that the mobilities are higher the more pure the nitrogen is further brought out in Figure (3.14). In this test the bell jar was purged four times with the prepurified nitrogen, and the currents obtained were very large compared to those obtained in the other tests.

Since the maximum currents in carbon dioxide were the space charge limited currents, it was thought that perhaps the maximum currents in nitrogen may have some meaning. These maximum values for all negative ion tests in nitrogen are listed in Table VI, and a log-log plot is made in Figure (3.15). The results were three straight lines which had slopes other than 2.0. This indicates that \( I_b = KE_b^\circ \) where \( K \) is a constant and \( \circ \) is the slope of the line on the log-log plot. Since the slope is not 2.0, mobilities cannot be calculated from equation (2.14). This deviation
from the theory is believed to be caused by a distorted space charge set up in the gas that does not easily form negative ions. This was discussed near the end of Section 1.3.
Figure (3.12)

PLATE CURRENT
vs.
FILAMENT TEMPERATURE

Negative Ions in
Nitrogen

Plate Current (Amps x 10^-10)

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>Plate Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
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</tr>
<tr>
<td>800</td>
<td></td>
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<td>1000</td>
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</tr>
<tr>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>Plate Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>80v</td>
<td></td>
</tr>
<tr>
<td>100v</td>
<td></td>
</tr>
<tr>
<td>120v</td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td></td>
</tr>
</tbody>
</table>

Temperature in Kelvin:
- 600 K
- 800 K
- 1000 K
- 1200 K
- 1400 K

Note: The graph illustrates how plate current changes with filament temperature for negative ions in nitrogen, with different curves for different electron-beam potentials.
Figure (3.13)

PLATE CURRENT vs.
FILAMENT TEMPERATURE

Negative Ions in
Nitrogen

Plate Current (Amps x 10^{-10})

Plate Current (Amps x 10^{-10})

Plate Current (Amps x 10^{-10})

Plate Current (Amps x 10^{-10})
Figure (3.14)

PLATE CURRENT vs. FILAMENT TEMPERATURE

Negative Ions in Nitrogen

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PLATE CURRENT (AMPS X 10^-10)

0 1300 1350 1400 1450 1500

EB=180v
EB=160v
EB=140v
EB=120v
EB=100v
EB= 80v
EB= 60v
### Table VI

**Maximum Points for Negative Ions in Nitrogen**

(I_\text{b} \text{ in units of amps \times 10^{-10}})

<table>
<thead>
<tr>
<th>E_\text{b} (volts)</th>
<th>(3.4) I_\text{b}</th>
<th>(3.12) I_\text{b}</th>
<th>(3.13) I_\text{b}</th>
<th>(3.14) I_\text{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>64</td>
<td>170</td>
<td>172</td>
<td>352</td>
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<tr>
<td>80</td>
<td>112</td>
<td>360</td>
<td>360</td>
<td>720</td>
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<td>100</td>
<td>182</td>
<td>660</td>
<td>660</td>
<td>1100</td>
</tr>
<tr>
<td>120</td>
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<td>1060</td>
<td>1080</td>
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<tr>
<td>140</td>
<td>430</td>
<td>1580</td>
<td>1600</td>
<td>3000</td>
</tr>
<tr>
<td>160</td>
<td>600</td>
<td>---</td>
<td>---</td>
<td>3950</td>
</tr>
<tr>
<td>180</td>
<td>780</td>
<td>---</td>
<td>---</td>
<td>5300</td>
</tr>
</tbody>
</table>
PLATE CURRENT vs PLATE VOLTAGE

Maximum Points
Negative Ions in Nitrogen

From Figures (3.12) & (3.13)
Slope = 2.66

From Figure (3.15)
Slope = 2.66

From Figure (3.14)
Slope = 8.14

PLATE VOLTAGE (VOLTS)
Table VII gives some values of current for positive ion emission in carbon dioxide. These tests were made successively as fast as possible at a constant filament temperature and varying $E_b$. The thing that should be noted from the table and from Figure (3.16) is that there seems to be a decay of the positive ion current as time progresses. The currents were steady and constant at first, but they soon began to decay. After a period of time the currents not only decayed, but they also became erratic.

The decaying and erratic nature of the positive ion currents is further illustrated by Figure (3.17). In these two tests an older filament was used. The top part of the figure shows the decay in nitrogen and the lower part in carbon dioxide. The same filament was used in both tests. There was a surge of positive ion current just as the filament burned out.
Table VII
Positive Ion Currents at a Temperature of 1490°C

<table>
<thead>
<tr>
<th>$E_b$ (volts)</th>
<th>(a) $I_b$</th>
<th>(b) $I_b$</th>
<th>(c) $I_b$</th>
<th>(d) $I_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>21</td>
<td>21</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>38</td>
<td>38</td>
<td>34</td>
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<td>100</td>
<td>60</td>
<td>60</td>
<td>50</td>
<td>48</td>
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<td>120</td>
<td>86</td>
<td>80</td>
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<td>160</td>
<td>156</td>
<td>128</td>
<td>120</td>
<td>116</td>
</tr>
<tr>
<td>180</td>
<td>200</td>
<td>160</td>
<td>152</td>
<td>140</td>
</tr>
</tbody>
</table>

($I_b$ in units of amps x 10^{-10}$)
Figure (3.16)

PLATE CURRENT
vs.
PLATE VOLTAGE

Points from Table VII

Positive Ions in Carbon Dioxide

Slope = 2.05
Figure (3.17)

ION CURRENT vs. TIME

Positive Ions in Nitrogen

\( E_b = 180\text{v} \)

Temperature = 1455\text{°C}

Age 6 hr 36 min

Age 7 hr 36 min

15 min

160 Amps \( \times 10^{-10} \)

50

120

Time

Positive Ions in Carbon Monoxide

\( E_b = 180\text{v} \)

Temperature = 1500\text{°C}

32 hr 40 min

160 Amps \( \times 10^{-10} \)

Time

Age

3 15 min

160

50
Figures (3.18), (3.19), and (3.20) show the results of three more positive ion tests made with new filaments in the period before the decay in the current became too noticeable. These curves do not level off as the negative ion curves in carbon dioxide did. This indicates that the tube was operating under a temperature limited condition and did not change to a space charge limited condition.

The maximum points from these tests are given in Table VIII, and the log-log plot is given in Figure (3.21). The line obtained from Figure (3.19) has a slope of 2.0 over the greatest part of its length, so mobilities were calculated from this data and listed in Table VIII. The only justification for this is the slope of 2.0, therefore these mobilities may have no meaning at all since it seems that the tube was operating under a temperature limited condition.

The record of ion current shown in Figure (3.22) was made immediately following the data in Figure (3.20). It should be noted that the current remained at a constant value for a short time before it began to decay. The decay was steady until the filament burned out. The current did not become nearly so erratic in this case. Figure (3.23) illustrates further the erratic and decaying nature of the positive ion current. Both Figures (3.22) and (3.23) show a surge of positive ion current just as the filament burned out.
Figure (3.18)

PLATE CURRENT vs. FILAMENT TEMPERATURE

Positive Ions in Carbon Dioxide

Plate Current (amps x 10^-10)

Brightness Temperature (°C)

E_b = 180v
E_b = 160v
E_b = 140v
E_b = 120v
E_b = 100v
E_b = 80v
E_b = 60v
Figure (3.19)

PLATE CURRENT
vs.
FILAMENT TEMPERATURE

Positive Ions in Nitrogen

PLATE CURRENT (AMPS x 10^-10)

BRIGHTNESS TEMPERATURE (°C)

EB = 180v
EB = 160v
EB = 140v
EB = 120v
EB = 100v
EB = 80v
EB = 60v
Figure (3.20)

PLATE CURRENT
vs.
FILAMENT TEMPERATURE

Positive Ions in Nitrogen

Plate Current (Amps x 10^-10)

BRIGHTNESS TEMPERATURE (°C)
Table VIII
Positive Ions in Carbon Dioxide

\( I_b \) in units of amps \( \times 10^{-10} \)

<table>
<thead>
<tr>
<th>( E_b ) (volts)</th>
<th>( I_b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>35.7</td>
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<td>100</td>
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<tr>
<td>160</td>
<td>130</td>
</tr>
<tr>
<td>180</td>
<td>164</td>
</tr>
</tbody>
</table>

Positive Ions in Nitrogen

\( I_b \) in units of amps \( \times 10^{-10} \)
\( k \) in units of \( 10^{-4} \) meters/sec per volt/meter

<table>
<thead>
<tr>
<th>( E_b ) (volts)</th>
<th>Figure (3.19) ( k )</th>
<th>Figure (3.20) ( I_b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>27</td>
<td>28.4</td>
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<td>.46</td>
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</tr>
<tr>
<td>140</td>
<td>140</td>
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<td>202</td>
</tr>
<tr>
<td>180</td>
<td>220</td>
<td>262</td>
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</tbody>
</table>

Average Mobility = 1.15 \( \times 10^{-4} \) meters/sec per volt/meter
Figure (3.22)

ION CURRENT vs. TIME

Positive Ions in Nitrogen

\[ E_b = 180 \text{V} \]

Temperature = 1500°C

Age 5 hr 52 min
Burn Out

100 Amperes \times 10^{10}

Age 3 hr 51

15 min

200

100
Figure (3.23)
ION CURRENT vs. TIME

Positive Ions in Carbon Dioxide
$E_b = 180\,\text{V}$
Temperature = 1500°C

Age 16
15 min
60 Amps x 10^{-10}

Continued Below

RLINE-ANGUS CO., INC. INDIANAPOLIS, IN. U.S.A.

ES

Age 10 hr 30 min
Turn Off

Time
15 min
60 Amps x 10^{-10}
Figures (3.24) and (3.25) show a hysteresis effect which was observed when the temperature was increased then decreased at a constant plate voltage. The effect was much more pronounced for nitrogen than for carbon dioxide, but it was clearly present in both gases. Data of this nature could not be obtained for positive ions because of the decay in the current. No explanation for the occurrence of this effect is known.
Figure (3.24)

PLATE CURRENT vs. FILAMENT TEMPERATURE

Negative Ions in Nitrogen

Ascending Temperature

Descending Temperature

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$E_b = 100V$

PLATE CURRENT (AMPS x 10^-10)

0 100 200 300 400 500

BRIGHTNESS TEMPERATURE (°C)

1300 1350 1400 1450 1500
Figure (3.25)

PLATE CURRENT vs. FILAMENT TEMPERATURE

Negative Ions in Carbon Dioxide

Ascending Temperature

Descending Temperature

BRIGHTNESS TEMPERATURE (°C)

PLATE CURRENT (AMPS x 10^-10)
3.4 SOURCES OF ERROR

Probably one of the greatest sources of error in the experiment were the convection currents set up in the inter-electrode space because of heating of the gas by the filament. The movement of the gas would cause the ions to be deflected from their regular paths and thus make ideal measurements impossible.

Errors may also have occurred in the current readings. The currents were produced by setting a voltage on the plate. This voltage could not be set at exactly the same value each time, and it was noticed that very small variations in the voltage caused a noticeable difference in the ion currents. The higher scales on the Ultrohmeter also made the readings more inaccurate.

The temperature variation along the length of the filament was another source of error. This variation meant that emission was uneven along the length of the filament. The variation was dependent on the individual filament, and there was no means of taking it into account.

The exact amount and nature of impurities in the gas itself were not known. The mobility of an ion moving in a gas depends a great deal on the amount of impurity in the gas, so this is another reason why experimentally determined values may not agree with published values.
Chapter 4

CONCLUSIONS

A comparison of the mobilities determined from equation (2.14) and the values given in Table II probably has very little or no meaning since the exact nature of the ions produced is not known and since the values given in Table II are the most probable values at 0°C (the exact temperature of the gas in the experiment is not known, but it was much higher than this).

Although no mobilities could be calculated for negative ions in nitrogen, it was observed that the mobilities were very high since they are proportional to the ion currents. It was noted that the currents became much higher as the nitrogen was made more pure. This indicates that many of the ions were free electrons throughout their existence in the tube. Some of the electrons probably became attached to impurities in the gas causing the average mobility to be lower than that of free electrons. Since nitrogen does not form negative ions, the fast moving electrons may have produced a great many positive ions while moving in the tube causing a distorted space charge to be set up in the interelectrode space. This may be the reason the tube did not follow the theoretical transition from a
temperature limited condition to a space charge limited condition.

In carbon dioxide the tube gave every indication of changing from temperature limited to space charge limited operation. The mobility of negative ions in carbon dioxide was calculated from equation (2.13) and found to be $1.7 \times 10^{-4}$ meters/second per volt/meter.

The data in Figures (3.5), (3.6), and (3.7) was all obtained from the same filament. The age of the filament at the beginning of the test in Figure (3.5) was 14 1/2 hours, and at the beginning of the test in Figure (3.7), it was 31 hours. The magnitudes of the currents obtained in all three tests were approximately the same. This means that the negative ion current is independent of the age of the filament. This is brought out for nitrogen by Figures (3.12) and (3.13) which were made with the same filament. Here again the currents have approximately the same magnitude in both tests.

Positive ion currents, however, do depend on the age of the filament. When positive ion currents are produced, they are constant for a time but then began to decay. At first the decay is steady, but soon the currents become very erratic and jumpy. The decay continues until the filament burns out. At a temperature of 1500°C the filament will burn out in a period of from two to five hours. One filament was in operation for almost thirty-four hours.
producing negative ion currents in the temperature range of 1300 to 1500°C. This filament was removed from the tube before it burned out. From this it might be concluded that the negative ions are emitted as electrons which may be replaced by other electrons from the external circuit. On the other hand, positive ions are produced from impurities in the filament or the filament material itself which cannot be replaced. This wearing away of the filament causes it to burn out after a short period of time. When the filament is new the material which produces the positive ions is plentiful and near the surface, so for a short time the positive ion currents are steady. After a while, however, the surface material is worn away, and the positive ions must come from the interior of the filament. The binding forces here are greater, so the current begins to decay and becomes erratic. This tearing away of the filament causes it to break.

In Section 1.2 it was mentioned that most positive ions from platinum are from alkaline impurities, and emission of platinum ions is observed only in a rush of current just before the filament burns out. In each case when a filament burned out there was a surge of current. This may have been a current caused by positive platinum ions.

In the positive ion tests there was no indication that the tube became space charge limited. In one of the tests a plot of the maximum points on log-log paper yielded a
straight line with slope of 2.0. A mobility for positive ions in nitrogen was calculated from the data and found to be \(1.15 \times 10^{-4}\) meters/second per volt/meter.

No explanation can be offered for the hysteresis effect produced when the temperature is first increased and then decreased at a constant plate voltage. It is possible that this is some effect caused by the space charge at atmospheric pressure.

It is recommended that if more work is done along these lines, a method be found to determine the type of ions moving in the gas. The only method of determining the accuracy of the experimental work is to compare the mobilities calculated from equation (2.13) with published values. This is only possible if the type of ion is known.
Appendix I

PROPERTIES OF THE GASES

Nitrogen

Nitrogen has an atomic number of 7 and an atomic weight of 14.008. One liter weighs 1.2506 grams. The water pumped nitrogen has an oxygen content of less than 0.5% by volume and is saturated with water vapor. The prepurified nitrogen is dry and the oxygen content is guaranteed to be less than 0.001%. The hydrogen content is also less than 0.001%.

Carbon Dioxide

Carbon dioxide has a molecular weight of 44.01. One liter weighs 1.9768 grams. It has a purity of 99.5%. The impurities are air and moisture.
Appendix II
PURGING OF THE BELL JAR

According to Dushman\(^1\) the number of molecules \(n\) in a cubic centimeter of a gas is

\[ n = 9.656 \times 10^{18} \frac{P_{\text{mm}}}{T} \]

where \(P_{\text{mm}}\) is the pressure in millimeters of mercury, and \(T\) is the absolute centigrade temperature. The number of molecules per cubic centimeter at 300°Abs and 694 mm Hg (atmospheric pressure in Tucson) is \(2.2 \times 10^{19}\).

At atmospheric pressure ions make about \(10^9\) impacts per second.\(^2\) In air approximately 21% of these collisions will be with oxygen molecules and approximately 79% with nitrogen and inert gases. If nitrogen is put into the bell jar the oxygen molecules must be considered impurities.

\(P = \) ultimate attainable pressure in mm Hg

\(y = \) number of impurity molecules per cc remaining in the gas after the ultimate pressure is reached. This is also the number of impurity molecules which will be in the system after it is brought back to atmospheric


pressure with a pure gas.

\[ b = \text{number of collisions that will occur with impurity molecules per second in a cc of gas}. \]

\[ N = \text{number of molecules per cc in the system when the ultimate pressure is attained}. \]

\[ y = \left(\%\ \text{impurity molecules per cc in the gas after it is brought back to atmospheric pressure}\right)\left(\frac{N}{100}\right) \]

\[ b = \left(\%\ \text{impurity molecules per cc in the gas after it is brought back to atmospheric pressure}\right)\left(\text{collision frequency}\right) \]

From the above information if the system is pumped to \(10^{-3}\) mm Hg (1 micron), the number of collisions with impurities will be \(3.64 \times 10^{-4}\). If the system is pumped to only \(2.5 \times 10^{-2}\) (25 microns) and purged three times, the number of collisions with impurities will be \(6.5 \times 10^{-5}\). This shows that the gas can be made more pure by a series of purgings than by a single evacuation and one purging.
BIBLIOGRAPHY


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