A New Method of Investigating Thermionic Cathodes

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Under certain conditions, the electron current from a thermionic cathode is determined by the positive ion current reaching it. Two methods of using this relation to measure the thermionic emission of a cathode in a gaseous discharge are described. The constants, $b_0=30,000$, $A=10$ for a thoriated tungsten filament, and $b_0=22,700$, $A=88$ for an oxide-coated cathode, were obtained by use of these methods. The zero-field emission of an oxide-coated cathode was found to be only about 10 percent of the current at which the cathode was normally operated in practical discharge tubes. The increased current is due to the influence at the cathode of an external field which is established by an increase in the rate of generation of positive ions. The emission increases linearly with field up to fields of 150 volts/cm. Use is made of an auxiliary discharge to determine the relative ionizing power of electrons of different velocities. With cumulative ionization predominating, the total ionizing power increases linearly with the accelerating potential of the electron for voltages above the resonance potential and up to about two or three times this value.

INTRODUCTION

As the voltage between a thermionic cathode and an anode of a high vacuum tube is increased, the current rises until finally it reaches a saturation value which corresponds to the thermionic emission of the cathode. A determination of this saturation value for different cathode temperatures furnishes an emission-temperature curve for the cathode. For cathodes having high electron emissivity, such as oxide-coated and thoriated-tungsten cathodes, the high voltage necessary to overcome electron space charge develops sufficient power to cause overheating of the tube. For this reason, it has been customary to measure the emission of such cathodes at temperatures below the operating temperature and to calculate the emission for higher temperatures by means of Richardson's or Dushman's equation.

When the tube contains gas and the applied voltage exceeds the ionization potential of the gas, ions are produced which neutralize the electron space charge and permit the large currents to flow at low voltages. However, energy from the discharge raises the temperature of the cathode, increasing its emission and the current tends to run away unless limited by some external means, such as a ballasting resistance. Under these conditions, it is impossible to obtain any definite saturation and therefore impossible to determine any definite emission value for a cathode operating in a gaseous discharge.

In the following paper there will be described a method of measuring the emission from a hot cathode in a gaseous discharge under operating conditions.

CONDITIONS FOR A DOUBLE CATHODE SHEATH

A few years ago, Langmuir[1] showed that a thermionic electrode, when placed in the plasma of a gas discharge and maintained at a negative potential of such low magnitude that electrons leaving it could not produce additional ions in the plasma, emitted an electron current of only a few milliamperes, although it was capable of emitting amperes. The electron current from the inserted thermionic electrode increased with the arc current, which produced the plasma, and it was shown that the number of electrons leaving the hot electrode was directly proportional to the number of positive ions reaching it. In the same paper, it was deduced from theoretical considerations that the sheath surrounding a thermionic electrode having a surplus of electron emission is actually a double sheath with an electron space charge close to the cathode followed by a positive ion space charge at the

[1] I. Langmuir, Phys. Rev. **33**, 954 (1929). See especially exp. 560, p. 983.

plasma edge. The relation between electron and positive ion current densities at the thermionic electrode was derived and found to be given by

$$I_e/I_p=(m_p/m_e)^{\frac{1}{2}}, \tag{1}$$

where I_e and I_p are respectively the electron and positive ion current densities and m_e and m_p the corresponding masses.

Application of this fundamental relation furnishes a new method of measuring the thermionic emission of cathodes, as well as the variation of electron emission with electric field, the disintegrating effect of positive ion bombardment and the relative ionizing power of electrons of different velocities.

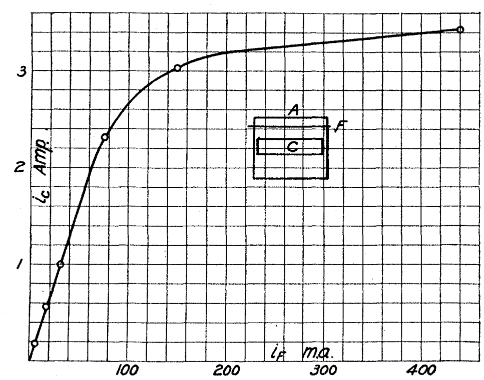

FIG. 1. Electron emission from C as function of arc current. C is 4 volts negative with respect to A. Arc volts $=E_{AF}=30$. Neon at 2 mm pressure.

Measurement of Zero-Field Emission

A typical tube used for measuring the electron emission of a cathode was a bulb 10 cm diameter in the center of which was a cylindrical anode, A, 3 cm long and 2.5 cm in diameter; concentric with this anode was a cylindrical oxide cathode, C, 6 mm in diameter and 2.5 cm long, which was heated by an internal tungsten coil. At a distance of 6 mm from C and parallel to its long axis was a tungsten filament, F, 0.18 mm diameter and 2.5 cm long. After the usual high vacuum exhaust, the tube was filled with neon to a pressure of 2 mm mercury. A potential of 30 volts was applied between F and A and the current limited by the temperature of F. C was made 4 volts negative to A. The positive ion current to it was found to increase linearly with increase of arc current between F and A. The cathode, C, was then heated by passing 10 amperes through the tungsten heater and the current from C measured as a function of the arc current, i_F. The results are shown in Fig. 1.

As long as C has a surplus electron emission, there is a double sheath with zero voltage gradient at C and the electron current, i_c, from it is limited by the ion current from the plasma so that i_c is directly proportional to i_F. This holds true up to $i_F=75$ m.a. Beyond this point, i_c does not increase as rapidly as i_F and the current is then limited by the electron emission of C. Thus the *value of* i_c *at the point of departure from linearity is a measure of the zero-field thermionic emission of the cathode* C. It should be noted in this connection that with an ionizing current of only one hundred milliamperes, sufficient ions are produced to permit an electron current from C of 2.5 amperes with an applied potential of only 2 volts. This is due in part to locating C close to F in a region of dense ionization and also to the fact that since the arc current is limited by the temperature of F, a high accelerating voltage could be used to obtain greater ionizing power of the electrons. The subsequent discussion will explain these arguments more fully.

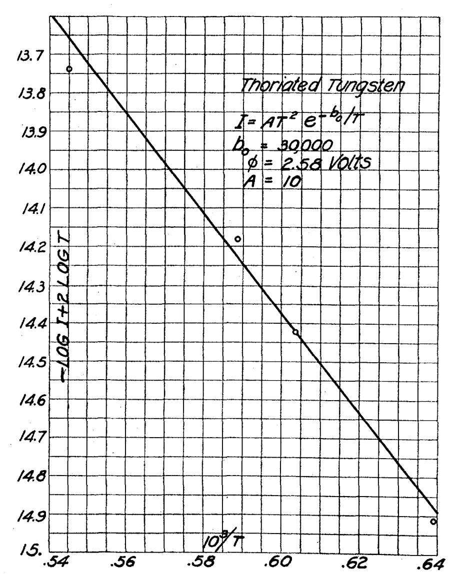

FIG. 2. Emission from thoriated tungsten filament in neon at 2 mm pressure measured by use of auxiliary discharge.

The emission from a thoriated tungsten filament as measured by Dr. L. R. Koller, of this laboratory, using this method, is reproduced in Fig. 2. It will be observed from the curve that the values of the emission constants are in good agreement with those obtained by other methods.

Field Emission

When the current from C becomes limited by its electron emission, it does not reach a flat saturation value but continues to increase slowly as the arc current (i.e., the positive ion current density) is increased. The slow approach to a saturation value is due, undoubtedly, partly to the nonhomogeneous nature of the surface and partly to unequal temperature distribution. However, the electric field established at the cathode when the ion current exceeds that required for the formation of a double sheath must have a decided influence on the electron current from C.

It is well known that the electron emission increases with field. At fields above 10,000 volts per cm, the increase can be accounted for by the Schottky effect.[2] However, at low fields the observed currents have been found to be much less than those expected from an extrapolation according to Schottky's equation, indicating that the zero-field emission is much less than that obtained from measurements made in the presence of a field. The effect of small fields is much more pronounced for composite cathodes, such as the thoriated tungsten, caesium on tungsten,[3] and oxide-coated cathodes. The results obtained in the present investigation also show that the zero-field emission from oxide-coated cathodes is actually only about ten percent of that at which the same cathodes are operated, without disintegration, in practical discharge tubes. The higher currents obtained in practice are the result of the effects of the

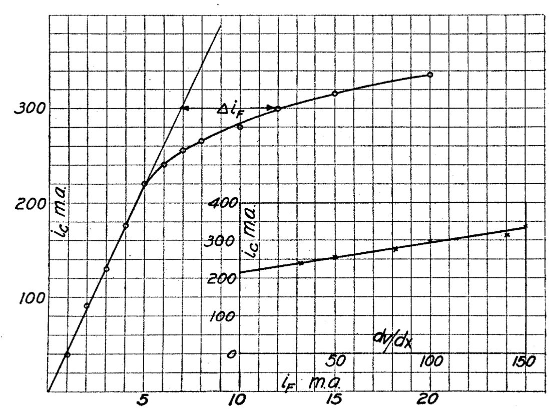

FIG. 3. Emission from unipotential oxide-coated cathode in mercury vapor. *Insert:* Emission *vs.* field at the cathode. $\Delta i_F = \Delta I_F \times$area of electrode.

external electric fields established in the cathode sheath by the creation of a positive ion space charge.

The field, E, at a plane electrode to which positive ions are flowing is given by[4]

$$E^2 = 7.57 \times 10^5 I_p V^{\frac{1}{2}} (m_p/m_e)^{\frac{1}{2}} \text{ volts/cm}, \quad (2)$$

where I_p is the positive ion current density in amperes per cm^2, V the voltage drop at the electrode in volts, and m_p/m_e the ratio of the mass of an ion to the mass of an electron.

If the electrode also emits electrons, the following similar expression can be derived easily

$$E^2 = 7.57 \times 10^5 \Delta I_p V^{\frac{1}{2}} (m_p/m_e)^{\frac{1}{2}}, \quad (3)$$

where ΔI_p is the positive ion current density in excess of that necessary to establish a double sheath.

The curve of Fig. 3 is the emission curve for an oxide-coated cathode, similar to the cathode, C, described above, taken in the presence of mercury vapor at room temperature. The zero-field emission is about 225 m.a. or about 35 m.a./cm^2. The curve in the inset is the emission as a function of field at the cathode. The field was determined by considering the cathode as a plane and applying Eq. (3). This procedure is not seriously in error as the cathode sheath is less than 0.2 mm thick.

The value of ΔI_p was obtained in the following manner. For the linear portion of the curve, Eq. (1) gives $I_e/I_p = (m_p/m_e)^{\frac{1}{2}} = 605$, but from

[2] For a summary of the effect of field on electron emission see K. T. Compton and I. Langmuir, Rev. Mod. Phys. **2**, 147 (1930).

[3] For an illustration of this see recent paper by J. B. Taylor and I. Langmuir, Phys. Rev. **44**, 436 (1933) in which they find that the zero-field emission may be much lower than that obtained by extrapolating, according to the Schottky slope, to zero fields the values obtained with higher fields.

[4] S. S. Mackeown, Phys. Rev. **34**, 612 (1929).

the curve, $I_e=43I_F$. Hence

$$I_p=43I_F/605. \quad (4)$$

The value of ΔI_p is then obtained from (4) by reading the value ΔI_F (see Fig. 3) corresponding to a given value I_e, where ΔI_F and I_e are the current densities corresponding to Δi_F and i_e, respectively.

The results show that the emission increases linearly with field strength up to fields of 150 volts per cm. For higher fields, the relation between emission and field strength must merge into that given by Schottky's equation.

Production of External Fields at Cathodes

The electron current, in excess of the zero-field current, which is obtained from a thermionic cathode in a practical discharge device, is due to the action of the external electric field at the cathode. This external field is created by an increase in cathode drop and also by an increase in positive ion current density at the cathode. The latter is much more effective in producing a field than the increased voltage drop *per se*.

As has already been shown, the electron current from a thermionic cathode is determined by the positive ion current to it as long as the cathode has a surplus electron emission. The number of positive ions, n_p, generated per second by an electron current, i_e, assuming single impact ionization, has been shown to be given by the relation[5]

$$n_p/i_e=K(V_c-V_i), \quad (5)$$

where V_c is the cathode drop and V_i the voltage necessary to cause ionization and K is a constant for low values of V_c, such as exist in thermionic discharges. If f is the fraction of the ions which reach the cathode, the positive ion current at the cathode is

$$i_p=i_e\cdot f\cdot K(V_c-V_i). \quad (6)$$

Although this equation has been shown to hold only for single impact ionization, it will be shown later that, while cumulative ionization existed in the tubes studied, an expression similar to (6) is valid for this case also.

[5] K. T. Compton and I. Langmuir, Rev. Mod. Phys. **2**, 125 (1930).

When the zero-field emission exceeds the arc current, both (1) and (6) must apply, and, hence, a simultaneous solution gives the conditions for the existence of a double sheath, which is

$$V_c-V_i=(m_e/m_p)^{\frac{1}{2}}/f\cdot K. \quad (7)$$

Since in this expression the only variable quantity is V_c, the latter must adjust itself to a definite value at which the electrons leaving the cathode generate a sufficient number of positive ions so that the number reaching the cathode will permit the electron current to leave it. As an illustration, let us calculate the voltage drop at the cathode of a hot cathode discharge in neon at 2 mm pressure. It will be shown later in this paper that, at this pressure, ions are formed by cumulative ionization and the value of V_i is about 16.5 volts, corresponding to the resonance potential. Moreover, since the free paths of the electrons are small compared to the tube dimensions, a value of K should be taken corresponding to the total ionizing power of the electrons. An estimated value of $K=0.02$ can be obtained from the results of Langmuir and Jones.[6] If we further assume that fifty percent[7] of the ions generated return to the cathode, we find by substituting these values in (7) that $V_c-V_i=0.5$ volt or $V_c=17.0$. A similar calculation for mercury for the case of ionization by single impact gives $K=0.06$ and $V_c-V_i=0.05$ volt. Although the values of the constants for mercury are less accurately known than for neon, it is certain that V_c-V_i is much less in the case of mercury. This is due to the fact that the probability of ionization is greater for mercury and also to the fact that due to the larger mass of the mercury ion fewer ions are needed to neutralize a given electron space charge.

When the arc current exceeds the zero-field emission of the cathode, the cathode drop increases in order to establish the field necessary to obtain the excess current. In order to illustrate the relative influence of ion current and cathode drop in establishing a field at the cathode, let

[6] I. Langmuir and H. A. Jones, Phys. Rev. **31**, 402 (1928).

[7] Since there is practically no recombination of positive ions and electrons in the space, all of the ions which are generated must disappear either at the electrodes or the tube walls. By the use of a collecting electrode at the wall, the total positive ion current to the walls was found to be the same order of magnitude as that to the cathode.

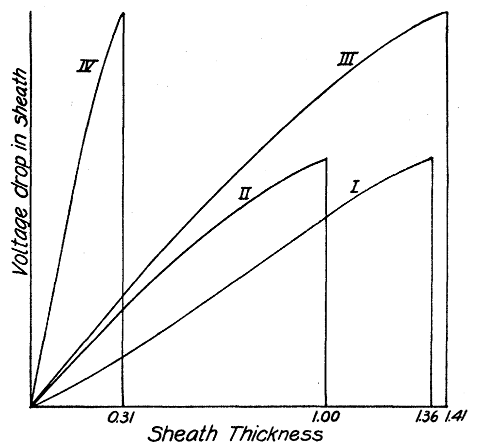

FIG. 4. Potential distribution in sheath. I, double sheath; II, non-emitting collector at 17 volts; III, non-emitting collector at 27 volts; IV, emitting electrode at 27 volts.

us consider the distribution of potential in a sheath under different conditions. Such a series of curves are plotted in Fig. 4.

Curve I shows the potential distribution in the double sheath at a plane cathode of a neon discharge at 2 mm pressure when the arc current is less than the zero-field emission of the cathode. Under these conditions, the voltage drop is 17 volts and the gradient is zero at both the cathode and plasma. The relation between positive ion and electron currents is that given by Eq. (1). As long as the conditions for a double sheath exist, both the voltage drop and potential distribution remain constant. The only change is a decrease in the thickness of the sheath as the current increases. A plane non-emitting electrode, at the same potential as the cathode, is surrounded by a positive ion sheath in which the voltage distribution is that shown in curve II. Under these conditions there is an electric field, the magnitude of which is given by Eq. (2). Also, the thickness of the sheath is reduced to 66.5 percent of that for the double sheath. If in the case of a non-emitting electrode the potential drop in the sheath is increased to 27 volts, corresponding to the value of the disintegration voltage of neon ions as determined by Hull,[8] the distribution of potential is that given in curve III. The thickness of the sheath is increased by about forty-one percent, but the field at the electrode is only twelve percent greater than for curve II.

If the arc current exceeds the field emission to such an extent that a cathode drop of 27 volts is required to create the necessary external field (as mentioned previously), then the positive ion current in the plasma is increased twenty-fold according to Eq. (5). In this case, the thickness of the sheath is reduced to 31 percent and the potential distribution, which is plotted in curve IV, shows a gradient at the cathode 4.7 times that in curve II.

These curves show that the primary cause of the field at the cathode in an arc discharge is an increase in the ion current density at the cathode rather than voltage drop as is evident from consideration of the significance of Eqs. (3) and (6). Thus, in attempting to interpret phenomena at the cathode of a gaseous discharge, it is helpful to consider the ion current density as governing the magnitude of the external field at the electrode.

From the above considerations it is seen that the operation of a cathode in a gaseous discharge may be divided into two phases based on the magnitude of the current in the arc. At currents less than the zero-field emission of the cathode, the primary electrons create ions necessary for the neutralization of electron space charge only and the cathode drop is independent of discharge current. At currents exceeding the zero-field emission, an extra supply of ions must be produced in order to create a positive ion space charge at the cathode. For the first phase, the ratio of i_p/i_e remains constant, while in the second the ratio increases with increase in arc current and thus necessitates an increased cathode drop.

Current Rating of Cathodes

From a consideration of the results obtained by Hull, it follows that a cathode may be operated without injury as long as the cathode drop is less than the critical disintegration voltage. Thus the maximum current at which a cathode may be safely operated is equal to the zero-field emission plus the field emission that can be obtained by the maximum field which can be created at the cathode without causing the cathode drop to exceed the disintegration voltage.

[8] A. W. Hull, Trans. A. I. E. E. 47, 753 (1928).

As has been pointed out earlier, the value of the field at the cathode depends not only on the cathode drop, but also on the positive ion current density. The following calculations illustrate the influence of the kind of gas on the production of a field. Let us compare the fields at a cathode operating in a neon discharge with those when it is operating in mercury. In both cases let us assume that 50 percent of the ions generated reach the cathode. It has previously been shown that under conditions for a double sheath, $V_c - V_i$ is 0.5 volt for neon and 0.05 volt for mercury.

No information is available for the voltages at which an oxide-coated cathode is disintegrated, but Hull[7] has found that neon ions with a velocity corresponding to 27 volts disintegrate thorium on tungsten and that the corresponding value for mercury is 17 volts. For a thoriated tungsten cathode, these values represent the maximum permissible cathode drop and when substituted for V_c in Eq. (6) give the maximum positive ion current at the cathode. For neon, this is found to be twenty times that required for a double sheath and one hundred and thirty times for mercury. If y represents this ratio, we can write $\Delta I_p = yI_p$ and, combining with Eq. (6) we obtain

$$\Delta I_p = y \cdot f \cdot I_e (m_e/m_p)^{\frac{1}{2}}. \quad (8)$$

Substitution of this expression for ΔI_p reduces Eq. (3) to

$$E^2 = 7.57 \times 10^5 y \cdot f \cdot I_e \cdot V^{\frac{1}{2}}. \quad (9)$$

Using the values of the constants given above, we find that at the upper limit of safe operation for a thoriated tungsten cathode the field at a cathode in a mercury discharge is more than ten times that in neon. Since the available emission is a function of the field, a cathode may be operated, without disintegration, at a much higher current in mercury than in neon. *Thus the safe current rating of a cathode in a gaseous discharge is not a characteristic of the cathode alone but is also dependent on the gas in which the discharge takes place.*

From Eq. (9) it is seen that any change in tube design which lowers the value of f will also lower the maximum field and therefore the current rating of the cathode. As the gas pressure is decreased, the positive ions are generated farther from the cathode and a smaller fraction of those generated reach it. This reduction in f decreases the maximum field and lowers the current rating of the cathode at the reduced pressure.

Probe Method of Measuring Zero-Field Emission

As has been pointed out, the ratio of i_p/i_e at the cathode is constant for arc currents less than the zero-field emission of the cathode. As the arc current is increased beyond the value corresponding to zero-field emission, i_p increases more rapidly than i_e so that the value of i_e at which an i_e *vs.* i_p curve departs from linearity is to be regarded as a measure of the zero-field emission. As has been shown above, this critical value of i_e may be determined by the use of an auxiliary arc. However, it is often much more practicable to use another method of determining this value of the zero-field emission. The random positive ion current, i_g, as measured by a probe in the plasma of the arc maintained by the cathode under investigation may be used as a measure of the positive ion current, i_p, actually reaching the cathode. The ratio i_p/i_g remains constant if the distribution of ion generation in the discharge is constant. Thus, under these conditions, the zero-field emission of the cathode will be indicated by the value of i_e at which the plot of i_e *vs.* i_g departs from a straight line. Since the cathode drop is constant for discharge currents less than the zero-field emission, the distribution of ion generation will remain the same over this range of discharge currents. If, however, the method of ion formation changes, as, for example, from single impact to cumulative ionization, a redistribution in the region of generation will take place and the interpretation of the results becomes more difficult.

The probe method is especially applicable to three electrode tubes, such as Thyratrons. Mr. C. H. Peck, of this laboratory, has used this method to measure the emission from the cathode of a FG 17 Thyratron tube. His measurements are given in Fig. 5. The ion current to the grid, which was made 12 volts negative to the anode, was measured as a function of arc current. The zero-field emission is seen to be about 250 m.a. Fig. 6 gives a zero-field emission *vs.* temperature

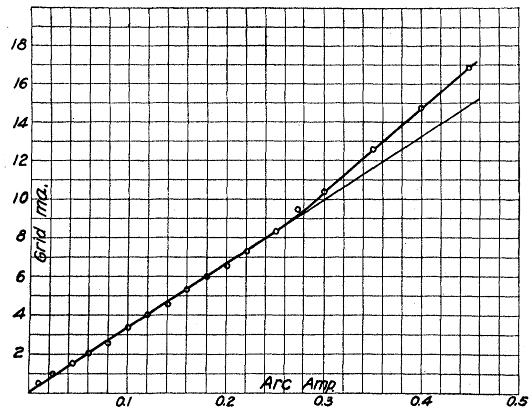

FIG. 5. Ion current to grid *vs.* arc current for FG 17 Thyratron. Grid 12 volts negative to anode.

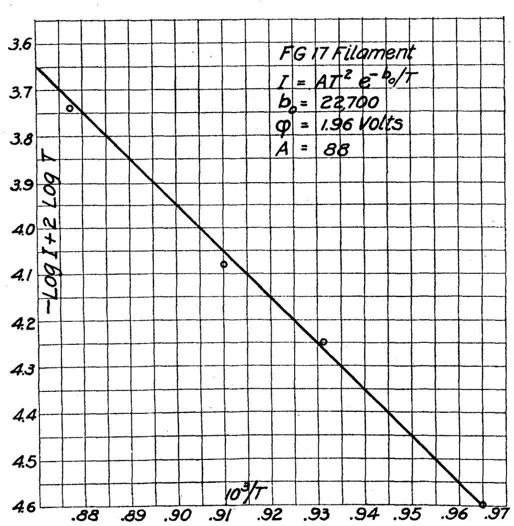

FIG. 6. Emission *vs.* temperature curve for cathode of FG 17 Thyratron.

curve for this cathode. The thermionic constants obtained from this curve are in good agreement with values obtained from measurements on oxide-coated cathodes in vacuum.

The probe method is not adapted for measuring the effect of external field on the emission, since at currents greater than the zero-field emission the cathode drop increases and causes a change in the distribution of ion generation.

IONIZING POWER OF ELECTRONS

Since the electron current from a thermionic electrode with or without field is determined primarily by the positive ion current to it, it follows that an electrode emitting a given number of electrons receives the same positive ion current regardless of the method by which the ions are formed. Consequently, this fact can be utilized to determine the relative ionizing power of electrons as a function of velocity. In a tube with an ionizing discharge and an electrode arrangement similar to the one described in the first part of this paper, the electron emission from the cathode, C, was measured as a function of the ionizing current from F for different ionizing voltages. The results of such a series of measurements are shown in Fig. 7. The tube contained neon at a pressure of 1 mm and C was 2 volts negative to the anode. The ionizing current necessary to liberate a given electron current from C is about three times greater for electrons having a velocity equivalent to 19.2 volts than for those at 23 volts. Thus 23 volt electrons are three times as effective in producing ions as those of 19.2 volts. In a similar manner, a comparison of the curves for the other voltages permits the relative ionizing power of the electrons to be plotted as a function of the

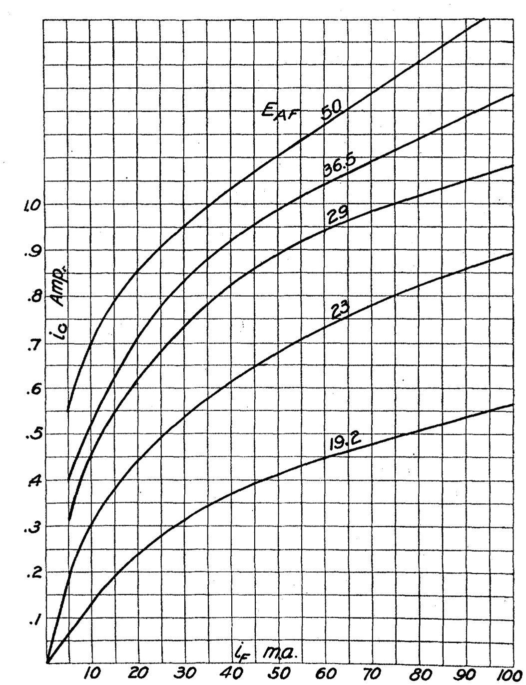

FIG. 7. Electron emission from C as function of auxiliary arc current and voltage. C is 2 volts negative to A. Neon at 1 mm pressure.

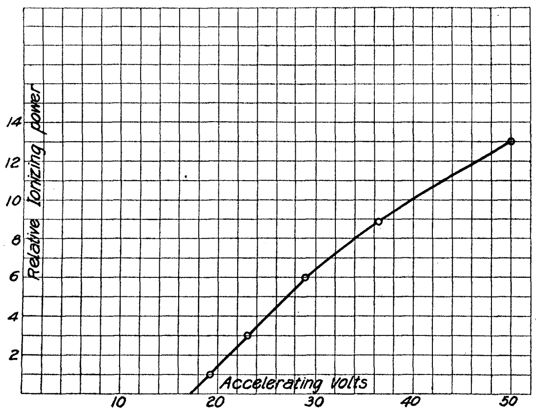

FIG. 8. Relative ionizing power of electrons in neon.

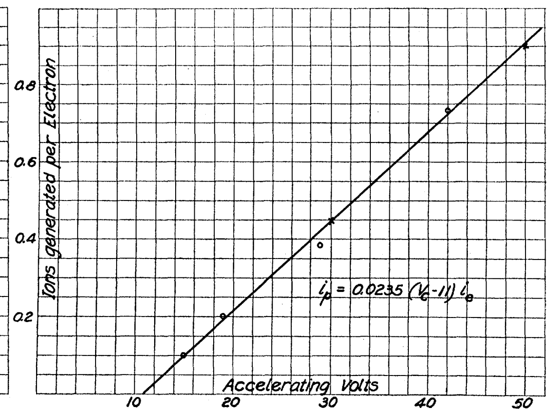

FIG. 9. Total ionizing power of electrons of different velocities in argon.

electron energy. This curve for neon is given in Fig. 8. Since other measurements with probes show that the energy of the primary electrons from F is decreased to a value less than V_i within a distance small compared to the tube dimensions, the relative ionizing power measured corresponds to the total number of positive ions formed or to β maximum as determined by Jones and Langmuir.[6] In the case of neon, the values obtained in the present investigation cannot be compared with the electron velocities used by them which were very much higher. However, it is possible to make such a comparison in the case of argon since the voltages used overlap those for which data are given by Jones and Langmuir. By adjusting the relative values of β maximum obtained in this investigation with those obtained by Jones and Langmuir, the two sets of measurements are found to agree. The results for argon at a pressure of 1 mm are shown in Fig. 9 and the crosses on the curve indicate results from the paper by Langmuir and Jones.

Since the voltage axis of curves in Figs. 8 and 9 are less than the values of V_i for neon and argon, respectively, it follows that ionization in these experiments must have been of the cumulative type. Although the relation given in Eq. (6) is based on the assumption that ionization occurs by single impact, it is interesting to find that the same relation is valid if V_i is replaced by a new constant of the order of the minimum excitation potential of the gas, which, as is shown by Figs. 8 and 9, is 11 volts for argon and 17 volts for neon.

Disintegration of Cathodes by Ion Bombardment

Although only qualitative results have been obtained, the use of a double cathode tube offers an excellent method of studying the effect of positive ion bombardment of a cathode surface. For example, cathode C can be bombarded by ions of any velocity produced by the discharge between F and A. The influence of this bombardment on the electron emission can then be determined by measuring the emission of C at a voltage sufficiently low to assume the absence of disintegration.

In conclusion, the writer would like to point out that in the above discussion emphasis has been placed on the methods, and only such experimental data have been given as were necessary to illustrate the application of these methods. Furthermore, no attempt has been made to include the modifications that would be necessary in order to take into account the effect of initial velocities. However, the manner in which this factor would modify the relations given in this paper is evident from the consideration of the equations derived by Langmuir.[9]

The writer wishes to thank Dr. I. Langmuir for many helpful discussions and Dr. S. Dushman for his assistance in the way of advice and criticism.

[9] I. Langmuir, Phys. Rev. **33**, 975 (1929).