The Dependence of the Energy Distribution in Field Emission upon the Geometry of the Collecting Surface

by

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Acknowledgments

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T. Pepper

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Introduction

Field currents[1] are the emission of electrons from a cold source. The emission is effected by an intense electric field. The investigation of spark potentials and spark lengths led to the discovery of field currents. R. W. Wood[2] in 1897 obtained field emission while endeavouring to produce an intense X-ray source. At first there was uncertainty as to the nature of the carriers of the electricity. Kinsley[3] contended that the carriers came neither from the gas in the chamber nor the metal in the electrodes. However it was almost immediately shown by Hobbs[4] that, at potentials lower than the minimum spark potential of the gas in question, the carriers of the electricity came from the metal and not the gas. For incandescent metals, however, J. J. Thomson[5] had previously shown in 1899 that the carriers were electrons.

Later work by Millikan and Eyring[5] led to an empirical field current equation

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1. also known as cold emission, autoelectronic emission.
2. R. W. Wood, Phy. Rev. 5, 1, 1897.
3. C. Kinsley, Phil. Mag. 9, 692, 1905.
4. G. M. Hobbs, Phil. Mag. 10, 617, 1905.
5. J. J. Thomson, Phil. Mag. 48, 547, 1899.
6. R. A. Millikan and C. F. Eyring, Phy. Rev., 27, 51, 1926.

$$i = C e^{-b/F} \tag{1}$$

where i is the field current

F is the field computed geometrically

C and b are constants of any particular surface.

The linear relationship between log i and $^1/F$ is readily seen by experiment.[7]

A theoretical relation, based on Quantum Mechanics and the Fermi Dirac distribution of electons in the metal, has been computed by Fowler and Nordheim.[8]

$$J = 1.55 \cdot 10^{-6} \left(F^2/w\right) 10^{-2.98 \cdot 10^7 w^{3/2} \varphi(y)/F} \tag{2}$$

where J emission current in amperes per square cm.

F electric field in volts per cm.- considered uniform.

w work function in electron volts

$y = 3.78 \cdot 10^{-4} (F/w)^{\frac{1}{2}}$ is the reduction in height of an image force potential barrier due to an impressed field F.

φ is an elliptic function of y - shown graphically in reference 7.

From (2) and values of φ it can be shown that for relatively small values of F, log J varies linearly with $^1/F$. For large values of F, however, of the order of 10^8 volts/cm the

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7. J.E.Henderson and R.K.Dahlstrom, Phy.Rev.,5,55,1939.Fig.4.
8. R. H. Fowler, L. Nordheim, Proc. Roy. Soc. A,119,P.173, 1928.

linear relation becomes only approximate. Equation (2) is computed for 0° A. There is much work now being undertaken to ascertain the temperature dependence of field currents.[9,10] To a close approximation it appears that they are independent of temperature.

The fields required for cold emission are of the order of 10^6 volts/cm. These are considerably less than those required for appreciable emission according to classical theory,[7] for, according to Schottky[11], the field strength must be of the order of 10^8 volts/cm in order that the image force may lower the potential barrier enough to allow a measurable number of electrons to leave the metal. However, according to wave mechanics, the electron has a finite probability of penetrating the potential barrier when the applied field has reduced the width of the latter sufficiently.[8] This requires fields of the order observed. The emission of the electrons from the metal is, therefore, a function of their velocity distribution within the metal and the transmission coefficient of the potential barrier.

For a simple triangular potential barrier the transmission coefficient is given by:[12]

$$D = e^{-\frac{BW^{3/2}}{F}} \qquad (3)$$

9. G. M. Fleming and J. E. Henderson, Phy. Rev. 10,58,1940.
10. W. B. Nottingham, Phy. Rev., 10, 58, 1940.
11. E. W. Muller, Zeit. F. Physik, Page 734, Vol.102, 1936.
12. F. R. Abbott and J. E. Henderson, Phy. Rev. 1, 56, 1939.

in which w is the work function of the electron

F is the electric field

B is a numerical constant

Integration of (3) over the entire range of the energies of the electrons and all values of the field over the emitting area gives the total current. The measured field emission should therefore be given by $i = \epsilon \int_0^\infty N(w)\, D(w)\, dw$ (4)

where $N(w)\,dw$ is the number of electrons, having kinetic energy corresponding to their normal velocity components between W and D + dW, which impinge internally on unit area of the surface in unit time and D(W) is the transmission coefficient, a function of the potential barrier. The assumption of the Fermi-Dirac statistics leads to values of N(W) and

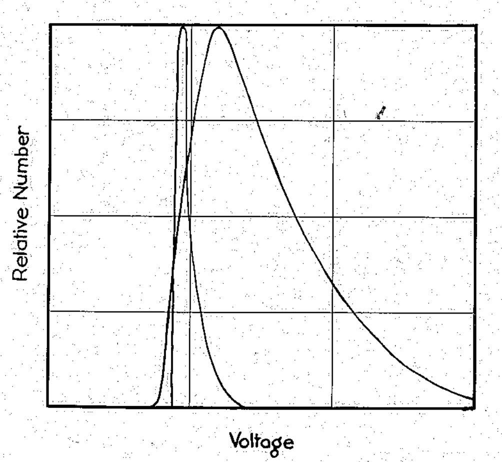


FIG.1 THEORETICAL AND OBSERVED DISTRIBUTIONS

the assumption of a plane surface and a simple triangular barrier to values of D(W) whence a theoretical distribution curve of normal energies is obtained closely resembling those found by experiment.[7,11] There are however two cases of deviation. Firstly, there is a less rapid drop to zero on both sides of the maximum than theory predicts. This is illustrated in Fig. 1, where the steeper curve represents the theoretical distribution of normal velocities and the more gradual curve with displaced maximum typifies the curve obtained experimentally. Secondly, examination of the shift in maximum as a function of the field strength has led to computed values of the emitting area of the order of 10^{-16} cm.^{2} which is much too small to account for the observed emission.[13] These deviations may be due to:

1) Failure of the Fermi-Dirac Statistics to describe correctly the velocity distribution in metals.
2) Assumption of a simple triangular potential barrier.
3) Assumption of a plane surface.
4) Geometry of the electrodes.

The Nature of the Present Problem

The present discussion deals with 3) and 4). In considering 3) it is to be noted that an error in predicting the emitting area may be due to the assumption of a plane emitting surface. Calculated field strength is less by a factor of from 10 - 100 than that required by theory to produce observed emission. This indicates a magnification of field intensity due to small irregularities (points) on the surface. The field currents from these points will give an energy distribution curve whose maximum will be at the maximum energy of the electrons.

13. K. V. Mackenzie and J. E. Henderson, Phy. Rev. 56, 857, 1939.

For the case of a hemispherical surface this is indicated in the following way.

The number of electrons/unit volume, whose velocities, regardless of direction, lie between V and V+ dV is given by:

$$\frac{8\pi\,(m^3/h^3)\,v^2\,dv}{e^{(\epsilon-\mu)/kT}+1} \qquad (4)$$

where ϵ is the kinetic energy of the electron and μ is a constant depending on the total number of electrons/unit vol.

The number of electrons/unit time which strike an area $r^2 d\omega$ with velocity V cos θ normal to the surface due to those electrons whose velocities lie between V and V+ dV and between the cones θ and $\theta + d\theta$ is given by:

$$\int_{\varphi=0}^{2\pi} \left\{\frac{\sin\theta\, d\theta\, d\varphi}{4\pi} f(v)\, dv\right\} v \left\{r^2\, d\omega \cos\theta\right\} \qquad (5)$$

The total electron emission from the surface of a sphere of

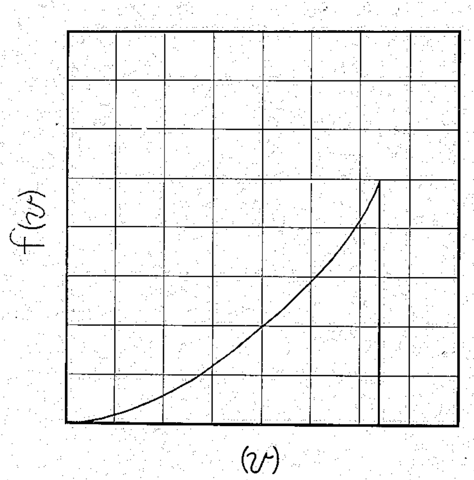


FIG.2 FERMI DIRAC DISTRIBUTION

unit radius is expressed as:

$$\int_{\omega=0}^{4\pi} \int_{\theta=0}^{\pi/2} \int_{v=0}^{\sqrt{2\mu/m}} \frac{1}{2} \sin\theta \cos\theta\, f(v)\, dv\, D(v\cos\theta)\, d\theta\, d\omega$$

where $D(V \cos \theta)$ is the transmission coefficient and u is the energy of the electron.

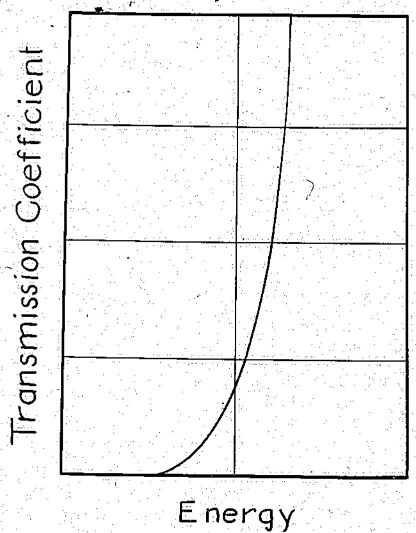


FIG 3

This total emission, i.e. the total number of electrons with velocities between V and V + dV which leave the sphere/unit time, assuming $D(V_n) = C_1 e^{C_2 V_n^2}$ where V_n is the normal velocity, now becomes

$$\int_V^{\sqrt{\frac{3u}{m}}} f(V)\,dV \int_{\theta=0}^{\pi/2} 2\pi \sin\theta \cos\theta \, D(V\cos\theta)\,d\theta$$

$$= C_1 \left(e^{C_2 V^2} - 1\right) f(V)\,dV \tag{7}$$

Equation (7) is the product of f(V)dV and $2\pi \sin\theta \cos\theta \, D(V\cos\theta)d\theta$ Both these factors increase with velocity as shown in Figs. 2 and 3. Therefore (7) most certainly reaches its maximum at maximum velocity of the electrons.

In considering 4) above it is possible that distribution curves may fail to show such an abrupt increase due to the geometry of the electrodes. This may not allow a proper measurement of "normal energies", since the variation in direction of emission leads to velocity components at angles other than 0 to the field and thus these may indicate electrons of too low velocities.

Research on electrode geometry should therefore serve the following purposes:

1) It would show whether or not the shift in maximum was a spurious effect and if so it would remove the discrepancy in area calculations.
2) The predicted sharp cut-off in the distribution curve, if obtained experimentally, would allow a good measurement of the work function of the collecting metal.[14]

The following investigators have varied the source and its geometry:

Eyring, Mackeown and Millikan[15] used tungsten, platinum and nickel points of varying bluntness.

Muller[11] worked with a tungsten point coated with successively thicker layers of absorbed barium, magnesium and caesium.

Henderson and Dahlstrom[7] mounted a cylindrical grid and plate coaxially with a fine wire tungsten filament.

The purpose of the present investigation is to observe whether, with conditions constant at the point source, there is a variation in measured energy distribution of field electrons accompanying progressive changes in the geometrical

14. W.H.Goss and J.E.Henderson, Phy.Rev.56,857,1939.

15. Eyring, Mackeown and Millikan, Phy.Rev. 31, 900, 1923.

design of the grid or/and plate; and whether under optimum conditions the observed energy distribution approaches the theoretical distribution with a sufficiently sharp cut-off to provide a better method of determining the work function of collecting metals.

Apparatus and Experimental Procedure

Attainment of a Vacuum

The pumping system consists of a fore-pump and an oil diffusion pump. The former, a Ceneo Hyvac, produces an optimum pressure of 10^{-3}mm. Hg as measured by an oil McLeod gauge. The latter is a two-stage three-compartment fractionating oil diffusion pump using Apieson A oil. The heat applied to each boiler was adjusted to prevent decomposition, which, for Apieson oils, occurs above 300° C.[16] Small nickel cylinders and nickel gauze were immersed in the oil of the boilers to prevent violent bubbling.[16] The two aspirator tubes were wrapped with asbestos pulp which caked to form a thermal insulator. This prevents excessive condensation of the oil vapours before they reach the nozzle. It was found that the immersion of a portion of the system in a dry ice ether freezing mixture gave as good vacuum conditions as a carbon trap cooled by the mixture. The freezing mixture at -77° C. reduces the vapour pressure of the Apiezon A to at least 2×10^{-8} mm. Charcoal was not used.

The tube, ionization gauge and cold trap are baked out in an asbestos oven built up around them of 1½ inch

16. J. A. Becker and E. K. Jaycox, Rev. Sc. Inst. 2,773,1931.

asbestos board. Four porcelain conical heaters in parallel on variable D.C. permit temperatures up to 500° C. to be used in the baking. The apparatus is usually baked from 24 to 48 hours at a temperature between $400-500^\circ$ C. During the interval between cutting off the oven and immersing the trap in the freezing mixture, oil vapour is condensed in an auxiliary recess trap filled with dry ice, thus preventing the vapour pressure in the tube from rising.

The metal parts of the tube and gauge are now degassed by an induction heater. The process of baking and degassing is repeated till the pressure is as low as possible -- $(2 - 3) \times 10^{-8}$ mm. Hg as measured by an ionization gauge. When the system is well degassed a stop cock between fore and diffusion pumps is closed and the gases and vapours pumped into two two-liter reservoirs for a month or more without building up the fore pressure more than a few microns.

Measurement of the Vacuum

The ionization gauge used is the standard triode type. The tungsten filament .005" in diameter is one loop inch in length, the grid $\frac{1}{4}$" mandrel of .01" diameter tungsten wire, the plate .005" nickel sheet in the form of a cylinder of $1\frac{1}{4}$" in length. By trial it was found that plate current varied linearly with grid current - at least up to I_g 15 m.a. Pressure is measured with I_g 2 m.a. For this the pressure in mm. of Hg is calculated to be ten times the plate current in amperes.

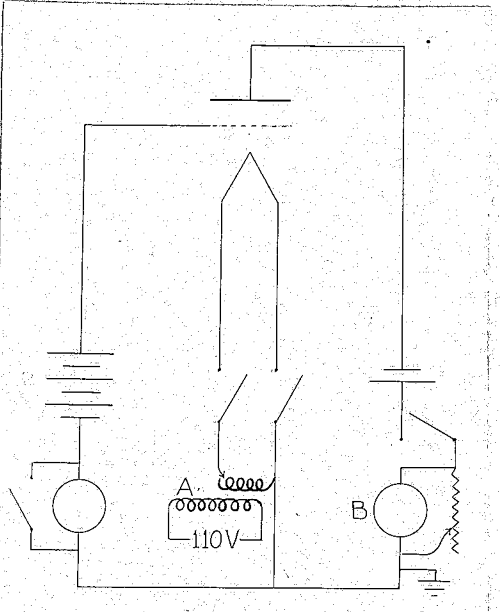


Fig 4. Gauge Circuit

The circuit is shown in Fig. 4. The filament is heated on the 6 - 12 volt range of a table transformer A; the grid is 135 V positive and the plate 45 volts negative relative to the filament. The galvonometer, B, used to measure the plate current will be described later. The degassing of the filament is accomplished by applying some 12 volts accross it for 30 minutes. The grid was degassed similarly by heating to a red glow for from a half to one hour. The plate was degassed using an induction heater. Even after considerable degassing, it was found that the pressure initially recorded when the filament was heated was of the order of 10^{-7} mm. Hg. However, within a minute or two the gas evolved from the filament is pumped out and the reading returns to the normal $(2 - 3) \times 10^{-8}$mm. Hg. Care must then be taken to allow the filament to heat for a few minutes before readings are made.

The Experimental Tube

First Construction:

The experimental tube initially constructed is shown in Fig. 5A. This was of the simplest possible design and consisted of a tungsten point, heated by bombardment from a separate coil filament, an accelerating grid and a collecting plate. The degassing of the point by bombardment

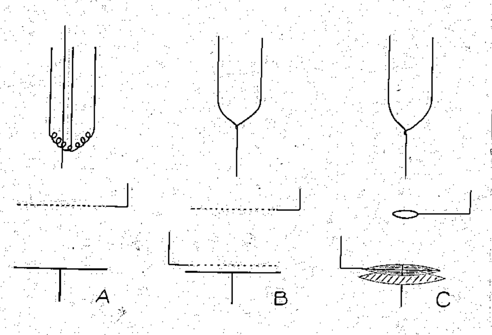


FIG 5 TUBE ELECTRODES

proved unsatisfactory due to its minuteness as a target and the formation of a retarding electron cloud around it. This design was therefore abandoned.

Second Construction:

The first attempt to construct a fine point was with a .65 mm diameter tungsten rod, mechanically sharpened on a grind stone till it was some 5 x 10^{-2} mm. in breadth. It was now dipped in molten $NaNO_2$ and etched down following the method described by Muller.[11] Initial irregularities in the point produced by the mechanical sharpening seemed unlikely to be removed. To hasten the etching the point was dipped in $NaNO_2$ crystals and held in an oxygen flame. The action was now very rapid and pits were eaten into the tungsten. These on further treatment could not be removed. Finally a much finer tungsten wire of .15 mm diameter was tapered by dipping in the $NaNO_2$. The latter was heated only moderately so as to prevent the pitting encountered in the previous trials. The point was viewed periodically under a 900 power oil immersion microscope until it had a radius of curvature of less than 10^{-3} mm in two mutually perpendicular planes. However it was very difficult to remove it from the oil on the slide without damaging it. The point finally used in the tube was $(5 - 10) \times 10^{-4}$ mm radius, tapered very evenly and showed no irregularities. It was spotwelded to the tungsten lead from the seal.

Degassing was accomplished by conduction. A second lead was clipped over the lead to the point and a variable voltage applied across the closed circuit thus formed. The point is then heated by conduction to a dull red for from a half to one hour.

The protection of the point is very important. There must be no discharge from it or it is immediately destroyed and, under a microscope, is seen to be twisted and turned into a blunt mass. For this reason a Tesla coil, when used for finding leaks, must never be brought near the leads to any of the tube electrodes. Should the point ever be left "floating" while a potential is applied to the accelerating grid, subsequent grounding will cause a sudden flow of current and destroy it.

The accelerating grid was a circular disk, two cm. in diameter, made of Ni gauze, 12 strands of .35 mm. diameter wire to the cm. Separation from the point was .8 mm.

The suppressor grid was of similar design and separated from the accelerating grid by 1.3 cm. These two grids and the filament were all mounted from a four press seal at one end of the tube. The lead from the accelerating grid was completely enclosed in a glass rod sealed to the tube thus minimizing parasitic currents.

The plate was led from the other end of the tube. It was a circular disk of 2.1 cm. diameter made of .35 mm. Ni plate. Around its periphery was spot-welded a Ni wire to give it rigidity and to remove any sharp edges liable to produce high fields.

All the electrodes were degassed by means of an induction heater. The metal parts were heated to a dull red till the grids and plate became very polished and clean.

Third Construction

The electrodes are shown in Fig. 5C. The characteristics of the point were as nearly as possible the same as for Fig. 5B. The accelerating grid consisted of a circular ring of Ni wire of about 6 mm. inner diameter mounted approximately 8 mm. from the point. The suppressor grid, 1.3 cm. from the former grid, consisted of three concentric Ni rings spotwelded as shown into a rigid frame by two mutually perpendicular Ni wires. The plate, 1 mm. from this grid, was the same as in the previous tube. From the geometry it is seen that all electrons from the point passing in a straight line through the accelerating grid would strike the plate.

The process of baking and degassing was similar to that of the previous tube.

The High Potential Source

The potential applied to the accelerating grid was supplied by a D.C. source constructed by Dr. W. Goss to produce from 0 to 20,000 volts. The essentials of the circuit are shown in Fig. 6. The filament of the rectifier

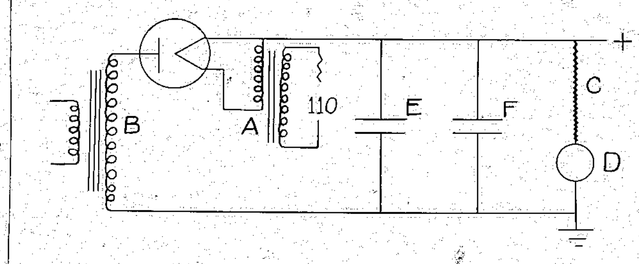


FIG 6. HIGH POTENTIAL SOURCE

tube is heated by two oil immersion transformers, A, connected in parallel. The high voltage is produced by a 20,000 volt Thordarson transformer, B, whose primary voltage is controlled by a variac. The voltage applied to the accelerating grid of the tube is calculated from the direct current, measured by the milliammeter D, flowing through the resistance C. C consists of 24 I.R.C. resistors of .4 megohms each, enclosed in glass to precent creepage. The resistors were accurate to within 5%.

The ripple in the voltage was minimized by two

.5 u.f.d. condensers E and F. The amount of the ripple can be calculated using a relation of Fortescue.[17]

$$C = \frac{I_0}{V_0} \cdot \frac{1}{\alpha f} \cdot \frac{\pi + 2\theta}{2\pi}$$

where C = capacity: here 1 u.f.d.

I_0, V_0 are miximum currents and voltages

$\theta = \sin^{-1}\frac{V_0}{V}$, of maximum value 1.

f is the frequency of the A.C.

α is the fractional voltage change.

The ripple αV_0 is then only a fraction of a percent of the applied voltage. This is well within the accuracy of the experiment.

Tube Measuring Circuits

Circuits for the measurement of field current and plate current are given in Fig. 7.

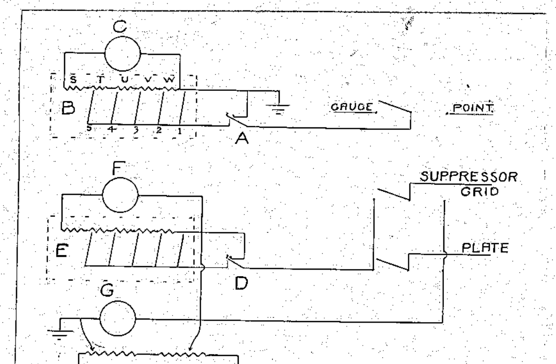


FIG 7.
MEASURING CIRCUIT

The field current from the point is directed either immediately to ground when the switch A is up, or through the galvanometer C to ground when the switch A is down. When a

17. High Voltage Physics, Methuen's Monographs on Physical Subjects.

high potential is applied to the grid the point must not be left floating even for as long as the interval between breaking the upper circuit at A and making the lower one. More than one point has been ruined in this way by the resulting surge of current. This is averted by keeping the upper circuit closed till the lower one is made; then breaking the upper circuit.

The galvanometer C is a Leeds and Northrup 2500b - sensitivity of .0005 microamperes. Its critical damping resistance is 10000 ohms. It is almost critically damped by the Ayrton shunt B whose resistances S, T, U, V, W are 1, 10, 100, 1000, 10000 ohms respectively. When switch 1 is closed the maximum current flows through the galvanometer. When switch 2, 3, 4 or 5 is closed the current through the galvanometer is diminished by a factor of 10, 100, 1000 or 10000 respectively. The currents are read by the deflection of the image of a cross hair on a 50 cm. translucent scale. The cross hair is a strand of wire fastened in front of the source of light and held one meter from the galvanometer. A 1- diopter lens was fixed to the galvanometer face so as to focus the cross hair on the scale, also one meter away. This device enabled the measurement of currents ranging between the limits of 5×10^{-10} and 5×10^{-5} amperes.

This same galvanometer was used also to measure the pressure indicated by the ionization gauge.

The plate current is measured similarly by galvanometer F, Leeds and Northrup 2500F, of critical damping resistance 22000 ohms. This is supplied by the Ayrton shunt E of construction similar to B but whose resistances are 2, 20, 200, 2000, 20000 ohms. Both galvanometers were calibrated before making any measurements. Plate bias is supplied by H, 4 storage batteries. The actual voltage of the plate relative to the point, read by the voltmeter G, is controlled by two resistors as shown.

This allows the measurement of plate current at any desired plate voltage.

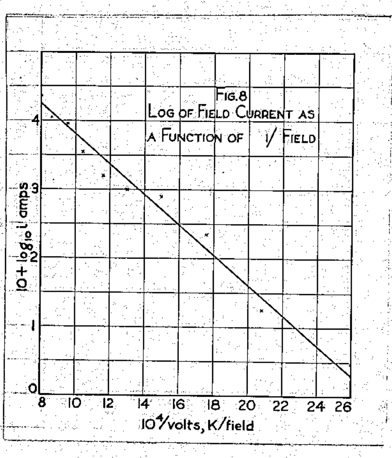
Data and Discussion of Results

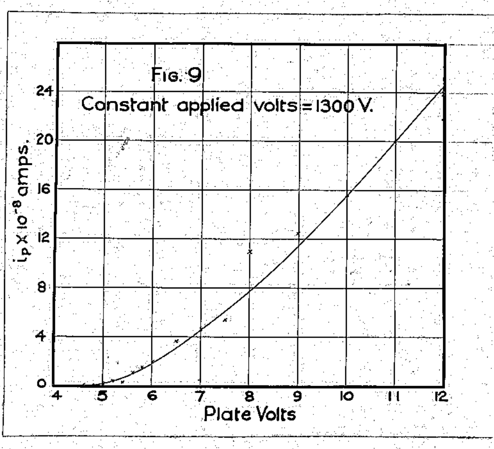
Measurements to date have been taken only from the two tubes illustrated in Fig. 5B and C.

Results using Tube 5B

The pressure was 2 x 10^{-8} mm. by the ionization gauge. The point had a radius of curvature of 10^{-3} mm. when it was mounted. There is no attempt to estimate the changes in size and form which it may subsequently have undergone. It was noticed that, as is customary with emission from a point,[11] the field current often changed, increased or decreased by a factor sometimes as high as ten. The formation and destruction of minute irregularities on the point at which the fields would be greater, would account for large changes in current. There is a tendency, however, upon repeated use, to wear down these microscopic irregularities, to reduce the field and resulting emission. The best results are obtained if the field is initially brought to its maximum value, allowed to remain steady for an hour or more, then decreased as current measurements are taken.

Another difficulty in taking measurements was that the current, even when fairly constant on the average, was continuously swinging up and down, changing by a factor up to three. Each value finally used was the average of some 20 readings of alternate maxima and minima of the current swings. This would still lead to an approximate value of the current as it was impossible to weight the readings at all. In view of these variations it was difficult to take a reliable set of readings. The graph of one such set is given in Fig. 8. Here the field current is plotted





as a fraction of the reciprocal of the applied voltage. No attempt is made to estimate the fields at the sources of emission for the radii of curvature of the emitting irregularities are undetermined. It is therefore assumed that, during such time as these irregularities remain unchanged, the field varies linearly as the applied field. Fig. 8 then also gives the variation of field current as a function of the of the field.

The relation between plate current and plate voltage is shown in Fig. 9. The collector comprised both the plate and suppressor grid since these were connected externally. Theoretically, as indicated in the introduction, the curve should rise <u>most</u> steeply at the <u>lowest</u> voltage effective in producing a current. This voltage should be the work function of the collector. The slope of Fig.9, however, increases throughout the range of measurement. At least two possible explanations may be offered.

Firstly, only the slightest impurity on the metal surface, according to Nottingham[10] only a fraction of a monomolecular layer is necessary, will change the work function considerably. For example, according to Reimann[18] a monomolecular layer of thorium, of work function 3.38 electron volts, on tungsten, of work function 4.54 electron volts, changes the work function of the emitter to 2.63 electron volts. Although the metal was cleaned as much as possible by baking and degassing it seems quite likely that oil vapours and gas pressure below 2×10^{-8} mm. Hg would be effective in changing the work function.

Secondly, as mentioned in the introduction, if the electrons do not strike the plane field of the collector at 0° angle, then their normal energy components will be less than their true energies. Since their normal energies are the measured quantities, the electrons will, therefore, have an

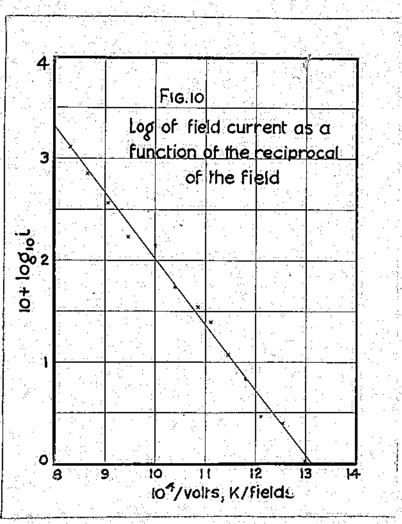
18. A. L. Reimann, Thermonic Emissions, p.12,13.

"apparent" energy too low. Consequently, higher plate voltages will be required to collect them. The maximum would then shift to higher applied potentials and the normal energy distribution curve would be distorted. It is, of course, impossible to say whether this "geometry effect" is responsible for the slope of the curve of Fig. 9; however, it appears that some such distorting factor exists.

Results using Tube 5C

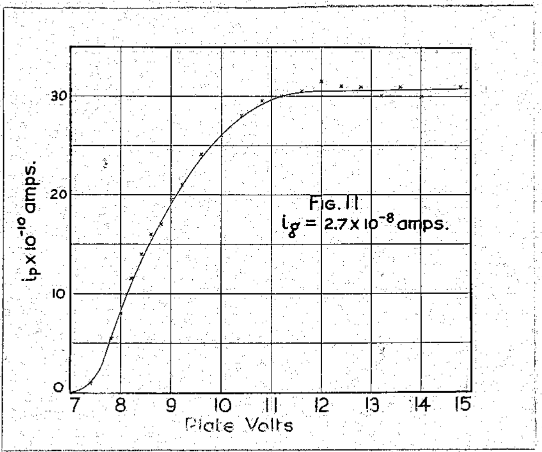
The pressure was (3 - 4) x 10^{-8} mm.Hg.

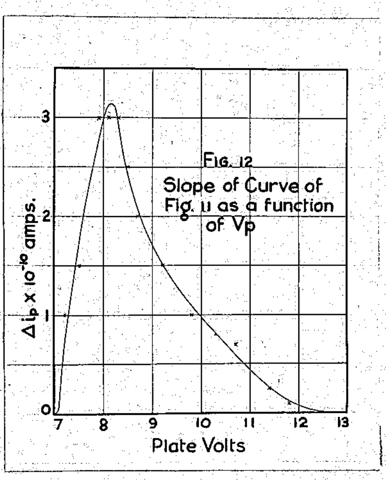
On the assumption again that the field at an emitting source whose form remains constant during the measurements, is proportional to the applied voltage, the variation of field current with field is again shown in Fig. 10. All readings were made in order of decreasing applied voltage.



The current was then much steadier than in the previous tube and at any one applied voltage remains steady almost indefinitely.

Figure 11 shows the relation between plate current and plate voltage, the collector as before consisting of plate and suppressor grid connected externally. With constant voltage on both accelerating grid and plate it was quite evident that field and plate currents varied together. Therefore great care was taken that readings were made only when the grid current was at a predetermined value 2.7 x 10^{-8} amps.





A number of trials were made with different values for the field and it was found that the plate current, plate voltage curve in each case varied as in Fig. 11. This curve has been differentiated and the slope as a function of the voltage is shown in Fig. 12. From this it can be seen that the maximum number of electrons were collected with plate voltage about 8.15. The shape of the curve agrees fairly well with that of Fig.1. However the electrons would appear to have been collected in an energy region some 3 volts lower than they ought to have been; the work function for Ni being given by C. W. Fox and R. M. Bowie[19] as 5.03 ±.05 electron

19. Reimann Thermionic Emission, p. 89.

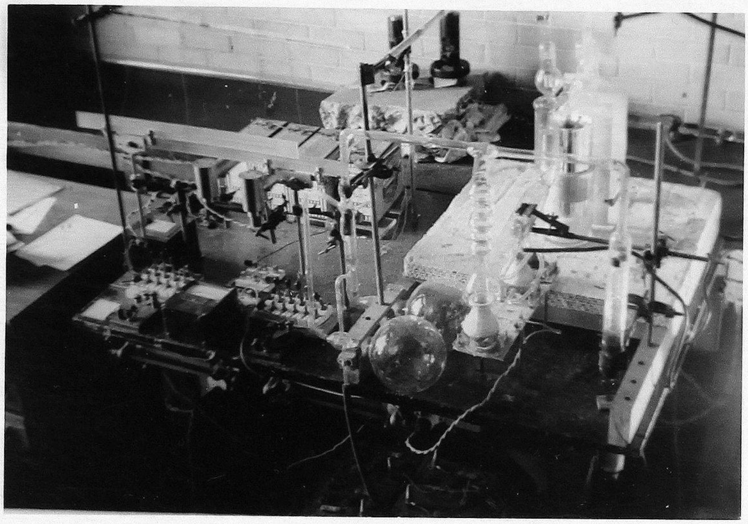
volts.

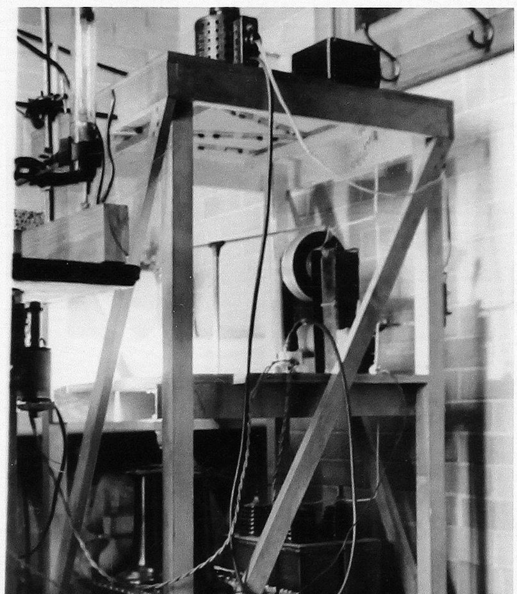
The same distorting factors cited in the discussion of the results of tube 5B are equally applicable here.

Conclusion

In conclusion it can be stated that although insufficient data is available to say just how much effect the plate geometry may have in distorting the normal energy distribution curve, nevertheless there does appear to be some distortion due to the plane fields so far applied. Conditions requisite for the measurement of work functions by the most suitable electrode geometry have certainly not yet been obtained.

APPARATUS





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