ELECTRON EMISSION FROM METALS IN INTENSE ELECTRIC FIELDS.

Thesis by

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Abstract.

The behavior of a fine wire placed axially in a cylindrical anode is investigated.

A brief account is given of the more recent literature dealing with the subject.

A quartz tube which has been found particularly suitable and convenient is described. As it is not possible to outgas the ends of the filament and the supports, these parts have been shielded from the field.

The usual source of high potential consisting of transformer, rectifier and condensers is used.

A description is given of a method for measuring potentials from a few volts up to 25000 volts. Use is made of a galvenometer and series resistance, and it is thought that the range can be extended to at least 100,000 volts.

With heat treated wires results are obtained in good agreement with earlier work, but it is shown that with such wires an appreciable current is obtained only after a break has occurred in the surface of the wire. The resulting characteristic depends only on the power available during the break and is shown to obey the empirical equation:

$$i = C\, e^{\frac{-b}{V}}$$

Microphotographs are presented which makes it plausible that the potential gradient may exceed 40 million volts/cm without producing currents in excess of 10^{-10} amperes and that the gradient is probably 10^{8} volts/cm or more when reasonably large currents are obtained.

With untreated wires a "loop phenomenon". is described which is thought to be due to positive ions from the anode. Heating the tube in an electric furnace is shown to have a great influence on the emission in this case. Microphotographs show that the diameter of such a wire decreases with use.

With thoroughly outgased wires the emission is not changed when the tube is submerged in liquid air, and the heating of the filament up to 1400 ^{o}K increases the emission only a few percent.

Introduction.

The present investigation was undertaken as a continuation of the work carried out at this Institute by Millikan and Eyring.[1] A comprehensive treatment of the history of the problem will be found in their paper and is therefore omitted here.

At about the same time Gossling published[2] the results of a long and careful investigation of the same subject, carried out in the laboratory of the General Electric Company of England. His results and conclusions were in good qualitative agreement with those of Millikan and Eyring, all observations being quite similar.

Some of the points which appeared to be definitely settled as a result of these and earlier experiments are:

1. The emission from cold metals is governed by the strength of the field at the surface, as is to be expected, and not by the applied potential.

1) R. A. Millikan & C. F. Eyring, Phys. Rev. 27 51, (1926).

2) B. S. Gossling, Phil. Mag. Vol. 1 609, (1926).

2. Emission occurs at a potential gradient, as calculated from the geometry of the field, which is smaller than predicted by Schottky's theory by a factor of the order of 100.

3. The emission is practically independent of the pressure below about 10^{-4} mm Hg.

4. The emission is nearly independent of the temperature of the metal up to about 1000° K. Beyond this temperature cold emission and thermal emission are not independent.

5. Local irregularities and impurities play an important role in the phenomenon and are perhaps able to account for the apparent discrepancy between the experimental results and the theory.

Since the publication of the papers referred to a great amount of work has been done on the problem by many investigators, experimental as well as theoretical.

3) Schottky, Zeits. f. Phys. 14, 80, (1923.)

The above results have been confirmed in all cases with the exception that del Rosario [4] concludes that cold emission is a gas phenomenon, but later obtains results in high vacuo which are in good agreement with those of other observers. However, from this work, which seems to have been performed with the utmost care, he concludes that the emission is determined, not by the gradient at the surface, but by the potential applied. This is in direct opposition to the conclusion reached by all other observers and is obviously erroneous since it is possible to obtain just as large currents with a few hundred volts applied to sharp points close together as with several hundred thousand volts applied between surfaces of large radii of curvature and suitable separation.

With apparatus built for another purpose at this Institute a current of a few milliamperes was obtained between 7.6 cm spheres 2 cm apart when over 500,000 volts were applied. [6]

4) C. del Rosario, Jour. Frank. Inst. 203,243, 1927.

5) " " " " " " 205,103, 1928.

6) C.C.Lauritsen and R. D. Bennett

An examination of how del Rosario reaches this erroneous conclusion will make clear just where the fallacy lies.

By treating wires of different diameters until they all give the same emission at a given potential he obtains nearly identical results for all the wires.

This is in no way surprising, for, as all observers have noted, the current-voltage curve may be shifted within very wide limits by suitable treatment of the wire.

The conclusion to be reached by this and other experiments is simply that the emission originates from one or a few spots, probably sharp points, and when the treatment has produced identical conditions, i.e., the same gradient, at points on the several wires, the current-voltage curves can be expected to be the same for all the wires, regardless of the diameter of the wire.

It simply means that the true voltage gradient is not the one calculated from the measured diameter of the wire,,but is to be determined from the actual point responsible for the emission. That this gradient may be at least ten times as great as the average value over the surface is made plausible by micro-

photographs presented in the present paper. On the basis of these pictures Oppenheimer[7] has estimated that the voltage gradient must exceed 40 million volt/cm at some point before the emission becomes sufficient to be measured.

N.A.De Bruyne[8] in continuing the work of Gossling confirms previous results and states that his results are not consistent with del Rosario's first theory. In addition he tests the effect of various impurities. He observes a small decrease when hydrogen is present and a large but temporary increase when the surface is coated with barium. A similar increase was obtained by Gossling with sodium nitrate and during the present investigation with pure sodium and magnesium.

Piersol[9] presents results on the effect of outgasing and current conditioning in good agreement with earlier work. In addition he shows that submerging the tube in liquid air has no noticeable influence on the behavior. This is in agreement with results obtained here and incidently published in the same issue.[10]

7) J.R.Oppenheimer, Proc.Nat.Ac. 14,363, 1928.

8) N.A.De Bruyne, Phil,Mag. 5,574, 1928.

9) R.J.Piersol, Phys. Rev. 31,441,1928.

10) C.C.Laurtisen & R.A.Millikan, Phys.Rev.31,914,1928.

Some of the results of the present investigation have already been presented[11] in particular the empirical relation between field-current and voltage gradient:

$$I = C e^{-\frac{b}{V}}$$

which was simultaneously published by Oppenheimer[12] but derived independently and from theoretical considerations based on the energy required to ionize the metal atoms in the emitting surface.

The same equation was later derived in a somewhat different manner by Fowler and Nordheim.[13]

Much of the data published by other observers has been plotted and found to fit the equation. Unfortunately the range over which measurements are given is usually too small to be of much value for this purpose. The equation was tested in a paper by Eyring, Mackeown and Millikan,[14] and was found to fit their experimental results as well as could be expected.

An interesting treatment based on Sommerfeld's application of Fermi's statistics is given by Houston.[15]

11) R.A.Millikan & C.C.Lauritsen, Proc.Nat.Ac.14,45,1928.

12) J.R.Oppenheimer, Phys.Rev. 31,431,1928.

13) R.H.Fowler & L.Nordheim, Proc.Roy.Soc.A 119,173,1928.

14) C.F.Eyring, S.S.Mackeown & R.A.Millikan, Phys.Rev.31,900, 1928.

15) W.Houston, Zeit. f. Phys. 47,33,1928.

This treatment brings out particularly the relative importance of the cold emission and the thermal emission at various temperatures and is shown to account satisfactorily for this phase of the results of Millikan and Eyring.

A theoretical treatment by Richardson leads to an equation containing $V^{\frac{1}{2}}$ in the denominator of the exponent instead of V. This equation does not conform with the experimental data as well as the one containing V.

Apparatus.

The Tube..

Throughout the present work the metal under investigation was in the form of a fine wire, usually tungsten .0012 to .0016 cm in diameter, placed at the axis of a cylindrical anode. Platinum wires and monocrystalline tungsten wires were also used. The general behavior was the same for all of these. Several different tubes and modifications were used, but only the one which was most satisfactory will be described here. The construction of this tube, which was built entirely of quartz is shown by figs 1 and 2. The fine wire is held between two copper support wires to which it is fastened by pinching. These support wires are in turn mounted by being pressed firmly into a narrow hook, formed in the tungsten seal-in wires. The seal-in wires are mounted in stepseals and are sufficiently long and flexible to exert a slight tension on the fine wire.

The support wires are surrounded by a tubular quartz extension from each end of the tube. These extensions serve not only to center the wire in the anode, but due to the charge which they collect they act also as electrostatic shields for the support wires and the ends of the wire under test. This last point is of great importance if reliable information on the effect of outgasing is to be obtained, for it is obviously not possible to heat

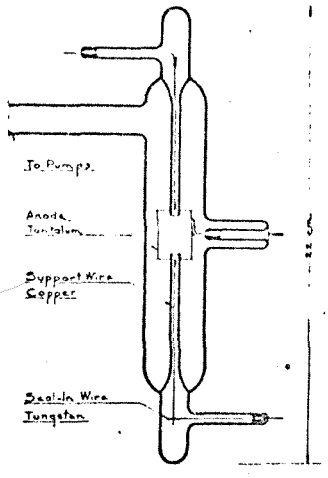
To Pumps
Anode
Tantalum
Support Wire
Copper
Seal-in Wire
Tungsten
Quartz Tube

Fig.-1

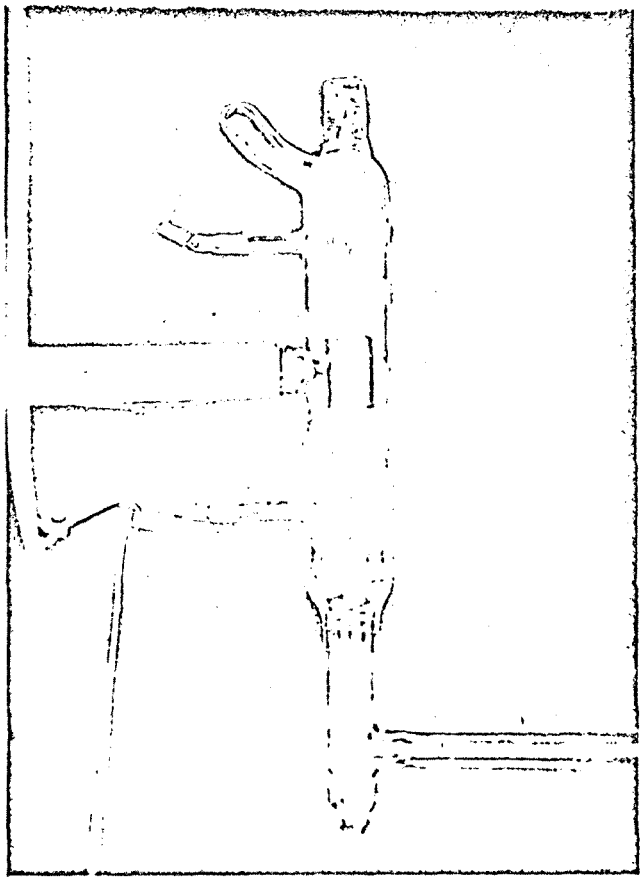

Fig.- 2

the ends of the wire to the same temperature as the central portion. This end-effect is due to the heat conduction of the supports, and is well known in thermionic work where it may readily be eliminated or corrected for. In the case of field currents this difficulty has generally been overlooked, but is here much more serious because practically the total emission may originate from a single spot any place on the wire. If this spot happens to be close to one end it is clear that heat treatment of the central portion of the wire may not produce the expected results. The present method has been found very effective in overcoming this difficulty.

As is evident from the sketch the construction is such that it is a very simple matter to change the wire when required. The two small extensions on the tube are blown out and the hooks forced open. The filament assembly can then be lifted out, and a new one put in its place, the whole operation taking but a few minutes. As more than thirty different wires have been used in this investigation it will be realized that this convenience is a matter of some importance.

The anode consists of a tantalum cylinder 1.6 cm in diameter and 2.5 cm long, supported from a side tube. The side tube contains a guardring, (not shown) which can be grounded. This, however, was found to be unnecessary.

The tube was used on the pumps, the pressure being maintained at 10^{-6} mm Hg or less as measured by an ionization gauge.

Source of Potential.

A maximum potential of 22000 volts was obtained by means of a 50 cycle transformer and a kenetron tube. Fig.3 shows the connections, and figs.4 and 5 show general views of the apparatus.

Two one-microfarad condensers inseries were placed across the output, and connection to the filament of the tube was made through a protective resistance of about .5 megohms, consisting of a glass tube about 1 meter long and filled with water. This resistance is necessary in order to limit the current when a crater breaks in the wire (see later). If the protective resistance is omitted, such a broak causes the wire to evaporate instantly provided sufficient power is available.

The necessary batteries, meters and rheostats for heating the filament were mounted on a support which was insulated for 25000 volts. This apparatus may be seen below the tube in fig. 4.

Measuring Equipment.

Up to 15000 volts the potential could be measured by

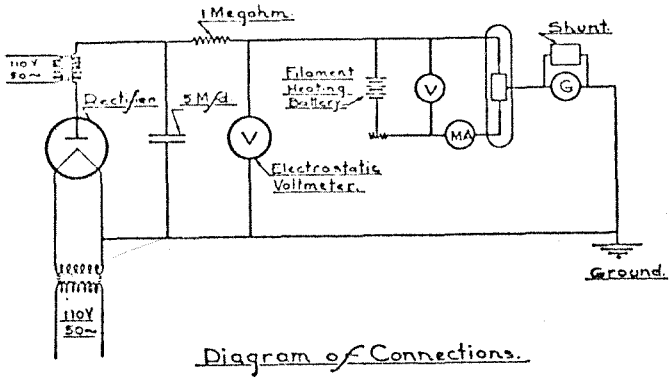

Diagram of Connections.

Fig. 3.

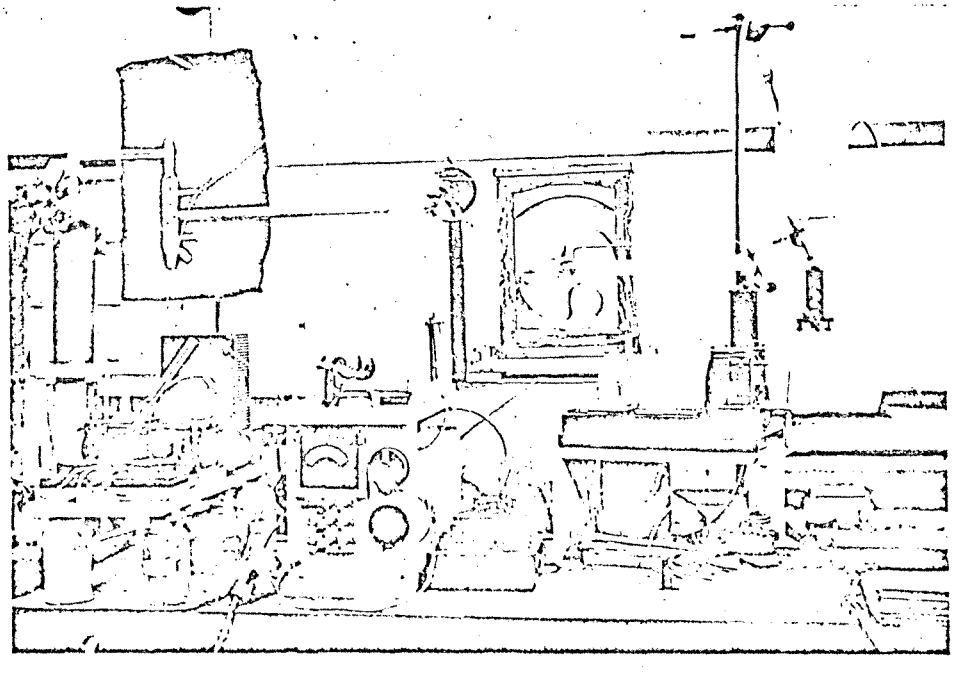

Fig. 4.

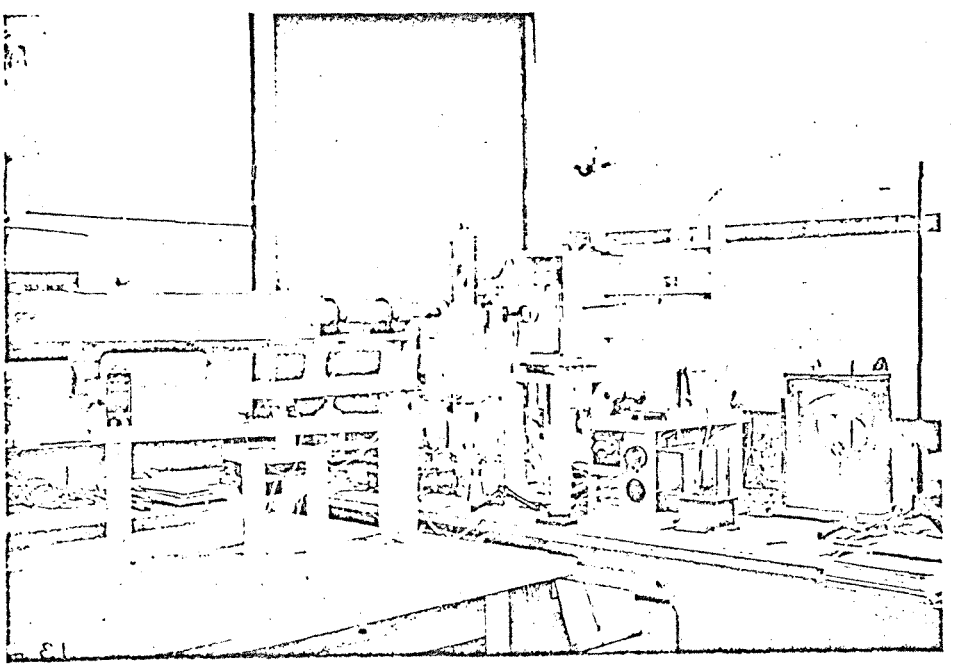

Fig. 5.

means of an electrostatic voltmeter which was first carefully calibrated.

Beyond this potential a galvonometer was used in series with a resistance of about 1000 megohms. This resistance consisted of a glass tube 2 cm in diameter and about 1 m long with large platinum electrodes and containing a mixture of about 90% xylol and 10% alcohol. As the resistance of such a mixture varies greatly with the temperature, the tube was provided with a narrow extension at the upper end. A scale was placed behind this extension on which the volumetric expansion could be read. A shunt across the measuring apparatus was calibrated directly in terms of this scale, so that small changes during a run could be compensated for conveniently. The measuring apparatus consisted of a galvanometer of medium sensitivity and an Ayrton shunt. The apparatus was adjusted to give full deflection for 250 volts. This range was carefully calibrated by means of batteries, and same point was checked before and after each run. By moving up two steps on the Ayrton shunt the range was thus 25000 volts. This range was checked up to 15000 volts against the electrostatic voltmeter. This method was found to be entirely satisfactory when checked continuously against a known battery potential of about 150 volts. It was actually used over the whole range from a few volts up to 22000 volts and could no doubt be used to at least 100000 volts.

The field current was measured by means of a second galvanometer with an Ayrton shunt and a Rawson Multimeter both connected between the anode and ground. The range used was from 10^{-10} to 10^{-2} amperes. Some measurements were made below this range on a tilted leaf electrometer, but this method was less satisfactory and somewhat unreliable due to the irregularities in the current.

Results.

Owing to the fact that the emission originates in one or more minute spots of more or less obscure physical character it is difficult, if not impossible, to obtain experimentally any accurate quantitative relation between the current density and the field strength. Although several hundred runs have been made it seems useless to present more than a few of the most characteristic results, for in all cases two important factors remain unknown. Those are, 1) the constant with which the potential is to be multiplied to obtain the actual potential gradient at the emitting point and 2) the area of the emitting surface.

The importance of these two factors is so great, that any attempt to determine the effect of other experimental conditions such as size of wire etc. seems quite hopeless at least with present methods.

There are, however, some characteristic features which are worthy of consideration, and the influence of certain

changes may be determined with some degree of reliability provided that it is possible to restore the original conditions in order to ascertain that the two above mentioned factors have not been disturbed in the meantime.

Emission from Heat Treated Wires.

The simplest case to deal with is that in which the outgasing of the tube and anode as well as of the cathode has been carried as far as practicable. In this case the phenomena observed are consistently the same and it is possible to obtain a reasonable explanation of what is going on. As the outgasing has to be done with some care, it is perhaps not amiss to describe the method which has been found to be most convenient.

When a new tube is used, it is first thoroughly cleaned in the usual manner and evacuated and heated for several hours at 500°C or more. The anode is then heated to a white heat by means of an induction furnace until no more gas is evolved. It is advisable to do this before the filament is introduced as it is apt to be damaged in the process. After the filament is introduced the baking is repeated and the surface layer of gas which has accumulated is removed by bombardment. This is most readily accomplished by gradually increasing the anode potential without heating the filament. Usually 10000 to 15000 volts produces enough current to make the anode uniformly white hot. It is important not to outgas the wire first

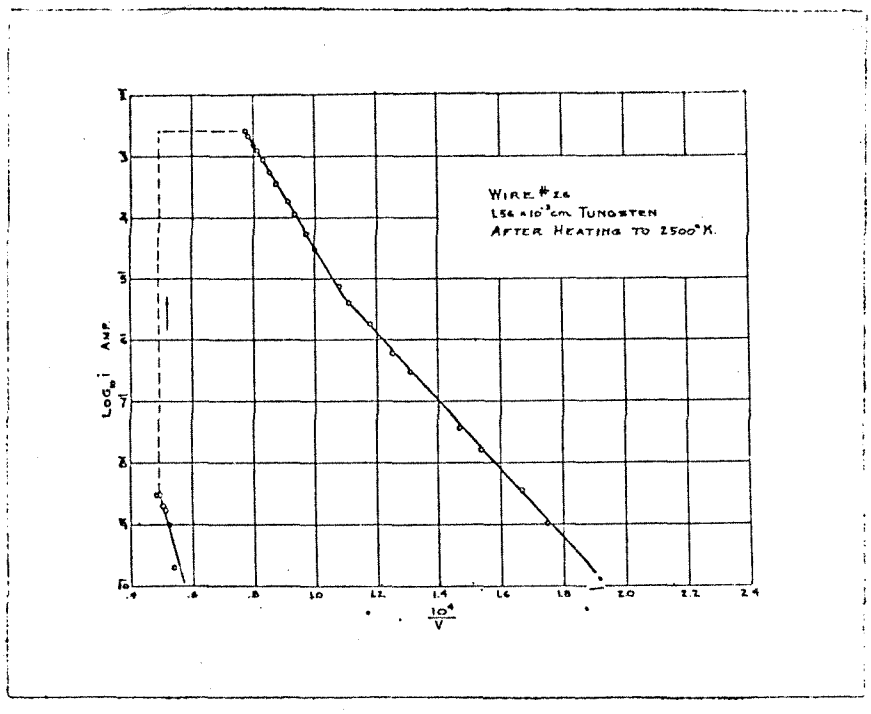
WIRE #16
1.56 x 10⁻³ cm. TUNGSTEN
AFTER HEATING TO 2500°K.
Log₁₀ i Amp.
10⁴/V
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4

Fig. 6.

no current is again obtained until 20,000 volts is exceeded; a new "break" occurs, and the wole process may be repeated almost indefinitely.

As already mentioned, the curve shown consists of two portions. This is usually but not always the case. Occasionally there is no break in the line, and in a few cases there were two or more breaks. This is thought to be explainable by considering that the emission originates from two or more spots, a straight portion on the curve corresponding to each point. At the lower potential all of the emission is from the smallest, sharpest point, where the potential-gradient factor is large (b small), and the area small (C small). Then as the potential is increased a point is reached where the emission from a larger, more rounded point predominates.

The two or more curves are of course additive, but owing to the logarithmic scale and the general lack of precision the nature of the curve at the bend can not disclose this.

It is reasonably certain that the violent increase in current described above is due to a mechanical break in the surface of the wire. This is rendered plausible by the fact that old wires, i.e. wires which have gone through the above described cycle a great number of times look pitted and scarred when viewed under a microscope. Figs.7 and 8 show two such wires magnified about 400 times. On such an old wire there are points where the field is at least ten times as great as the average. For the average field we have for a .0016 cm wire:

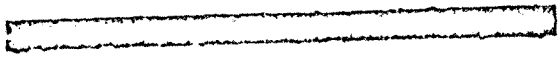

Fig. 7.

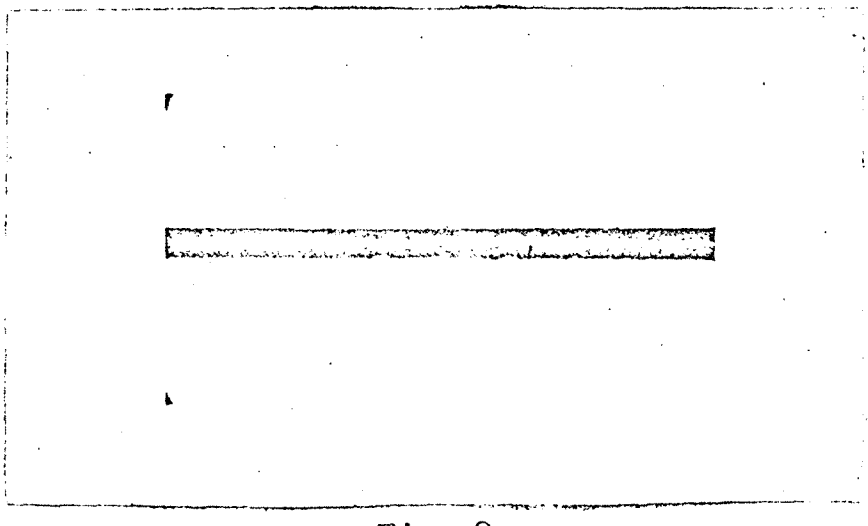

Fig. 8.

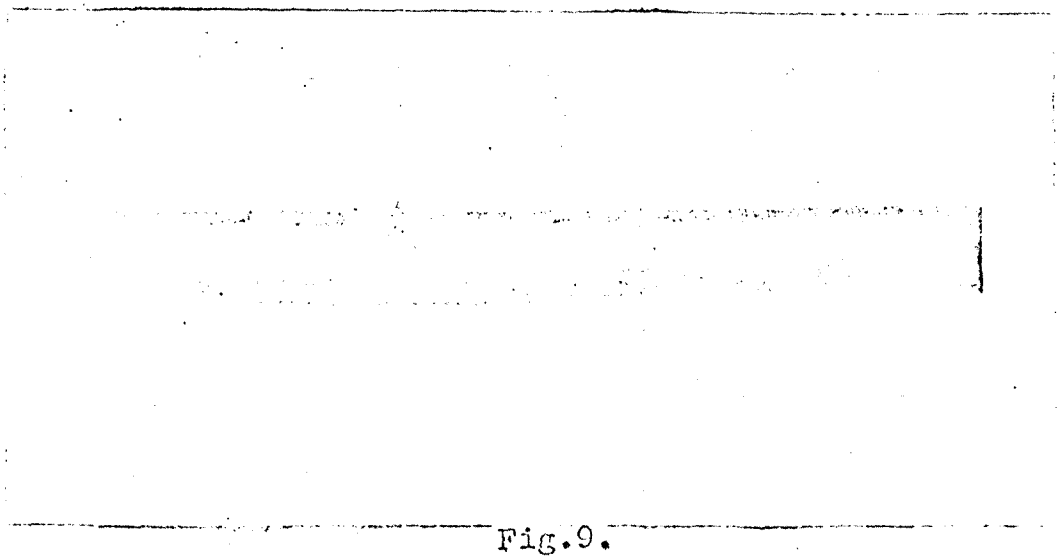

Fig.9.

$$F = \frac{V}{r \log \frac{R}{r}} = 181\ V$$

Where: r = radius of wire, R = radius of anode, V = potential.

With 22,000 volts applied this gives an average potential over the surface of 4 million volts/cm. When it is remembered that this is still the condition under which we obtain the small and perhaps uncertain current corresponding to the left branch of fig. 6, it is reasonable to assert that the gradient is considerably greater at the points responsible for the emission giving the right branch of the same figure.

Perhaps even more convincing is the evidence presented in fig. 9. This wire had been used only a few times and was removed from the tube intact. The picture was taken at the point of the wire where the emission last observed originated. This was judged by the position of the hot spot on the anode. It does not seem unlikely that the potential gradient at the sharpest point exceeds 100 million volts/cm.

Emission from Untreated Wires.

This case is considerably more complicated due to the still greater uncertainty as to the condition of the surface. As has been shown by many observers, large

currents are obtained at very low potential at first, but with continued use the curve shifts towards higher potential i.e. to the left in the present plots, and simultaneously the slope increases. This is what would happen if the emission originates from very sharp points which were gradually torn off or rounded down.

A phenomenon which has often been observed with untreated, but never with treated wires, is shown in fig.10. The curve is accurately reproducible and the currents corresponding to the upper curve were remarkably constant even over periods of many hours. The curve is obtained by maintaining the potential constant for several minutes before the current reading is taken. At the higher potentials the current becomes more and more unsteady until finally at some critical potential it begins to increase steadily but very slowly. In the course of an hour or more the current again becomes steady but at a value which may be several hundred times greater than before.

Decreasing the potential from this point produces the upper curve in fig. 10. The curve in this part of the cycle is, as already mentioned, exceptionally steady. In one case a reading, close to the lower end of this curve, remained constant for 36 hours, the potential being on continuously during this time.

If however, the potential is decreased below a

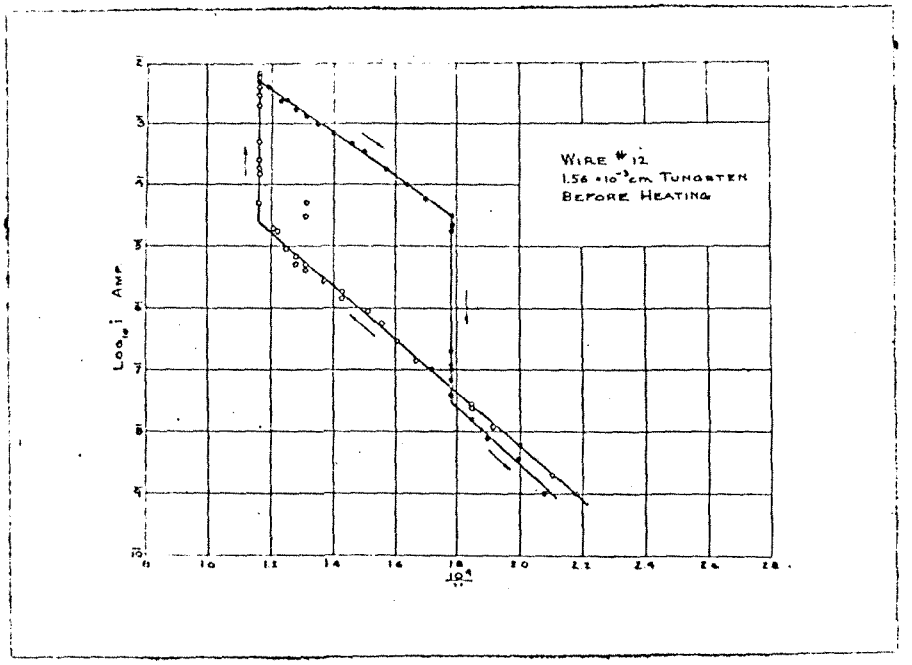

Fig.10.

certain critical value, then the current decreases very slowly until the original value for this point has been reached.

The process is repeatable in its general features, although the curves usually shift somewhat, one way or the other.

It was suspected that the condition of the anode played some part in producing this loop, particularly since the current at the critical points is very nearly sufficient to produce a red hot spot on the anode, and thus positive ions might well be liberated.

To test this idea, the whole tube was placed in an electric furnace and the temperature gradually increased to about 500°C while the potential was kept constant. It was found that from the lower curve in fig. 10 the current increased with the temperature and decreased again when the temperature was lowered, provided that the current had not in the meantime exceeded a certain value. If the current was permitted to exceed this value, it would increase, irrespective of the temperature, and become steady in the neighborhood of the upper curve in fig. 10.

A slight decrease in current was obtained when conditions corresponded to this upper part of the cycle and the tube was heated as before.

That these changes are not due to the increased temperature of the filament produced by the furnace is clear from the work of many investigators,[1, 2] and has been checked repeatedly in the present work. Thus in fig. 11 the increase in current with temperature up to about 1400°K amounts to only a few percent. Fig. 12 shows that submerging the tube in liquid air has no effect. One is therefore forced to the conclusion that either positive ions or gas from the anode are responsible for this cycle, which reminds one strongly of a similar phenomenon, well known in thermionic work.

It is evident that this phase could be invesitgated more satisfactorily with apparatus designed so that the anode temperature could be independently controlled over a wide range.

Figs. 13 and 14 show two filaments made from the same piece of tungsten wire and both taken with the same magnification. The one shown in fig. 13 was thoroughly outgased before any potential was applied. The surface has a mirrorlike smoothness, except for a few cracks like the one shown. The filament shown in fig. 14 was not outgased, but currents of several milliamperes was drawn from it for many hours. As will be seen the diameter has been reduced by about 40% in a very uniform manner.

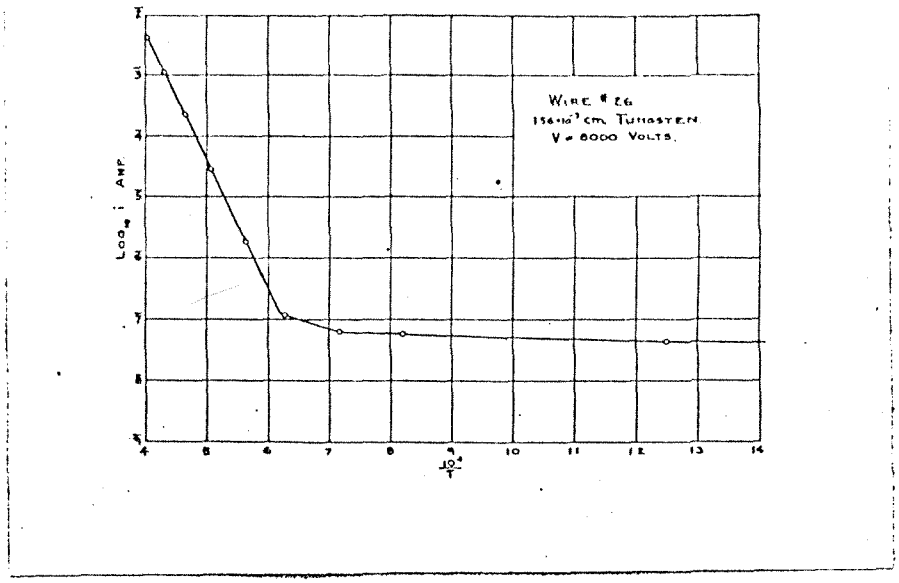
Wire # E6
1.56×10⁻³ cm. Tungsten
V = 8000 Volts.
Log₁₀ i Amp.
10⁴/T

Fig. 11.

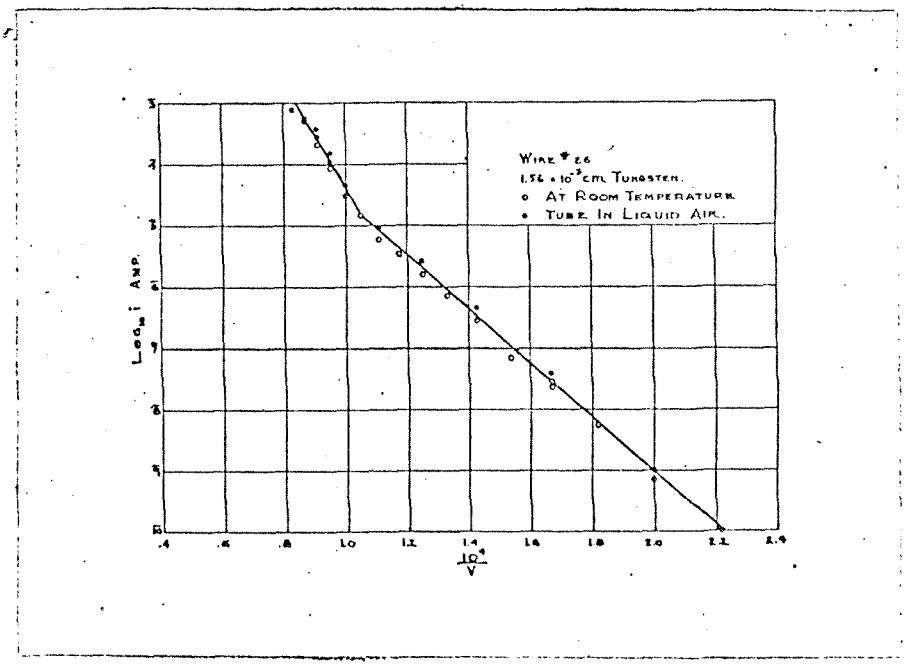
Wire # E6
1.56 × 10⁻³ cm. Tungsten.
o At Room Temperature.
• Tube In Liquid Air.
Log₁₀ i Amp.
10⁴/V

Fig. 12.

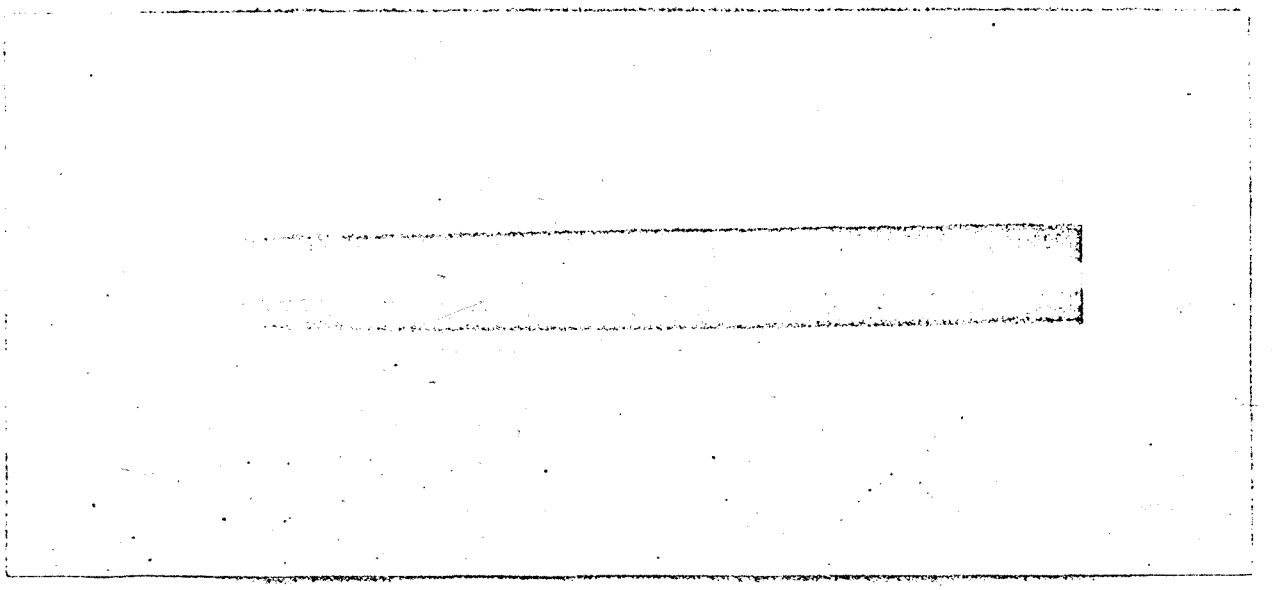

Fig. 13.

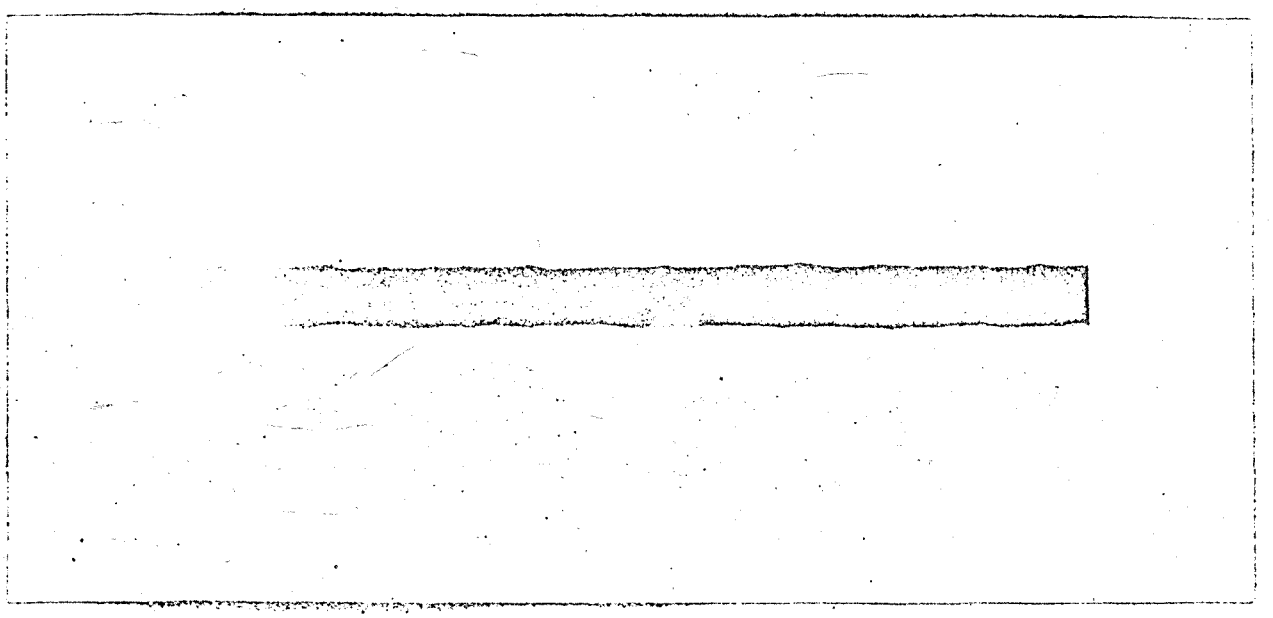

Fig. 14.

The material thus removed no doubt carries a small part of the current, but most of it ultimately finds its way to the walls of the tube, where it forms a minute layer, giving the walls a blue-violet tint. That the diameter remains so uniform leads one to think that the material is torn off where the field is greatest i. e. the high spots are continually removed.

Appearance of the Tube.

When a new wire is first put into use and the potential gradually increased until the current is of the order of 10^{-6} amperes, there is usually a very large number of blue spots on the walls of the tube, often covering quite uniformly the whole section above and below the anode.

With continued use the spots become fewer in number and it is not uncommon to see a single large bright blue spot on the wall.

Such a spot is usually eliptical as is to be expected from the form of the field, and while it varies in intensity, it remains often in the same place. Figs. 16 and 17 are typical of such spots. They are photographs of the tube shown in fig. 15. The filament in this tube was about 3 cm longer then the anode, and for this reason the spots often occurred on the glass rather than on the

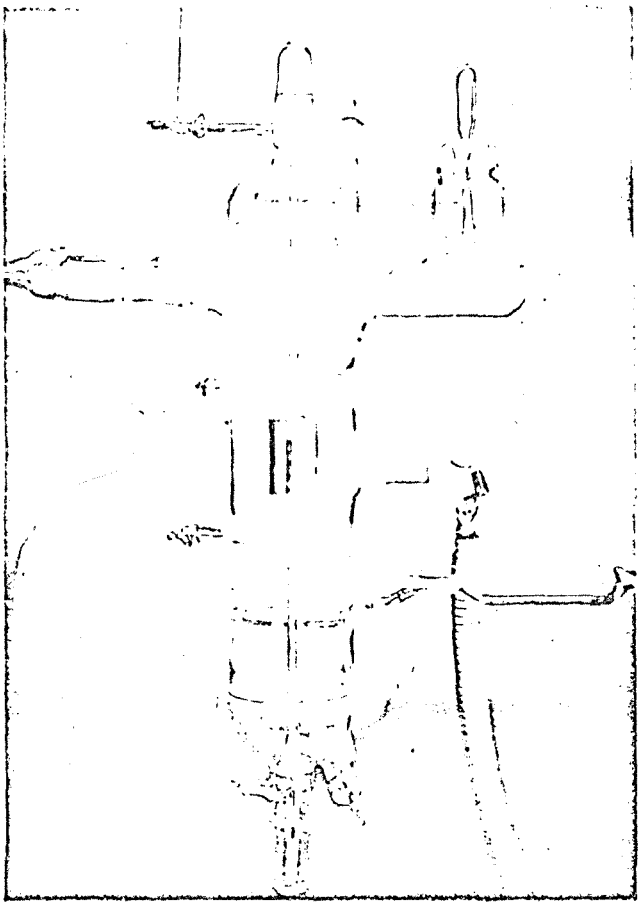

Fig. 15.

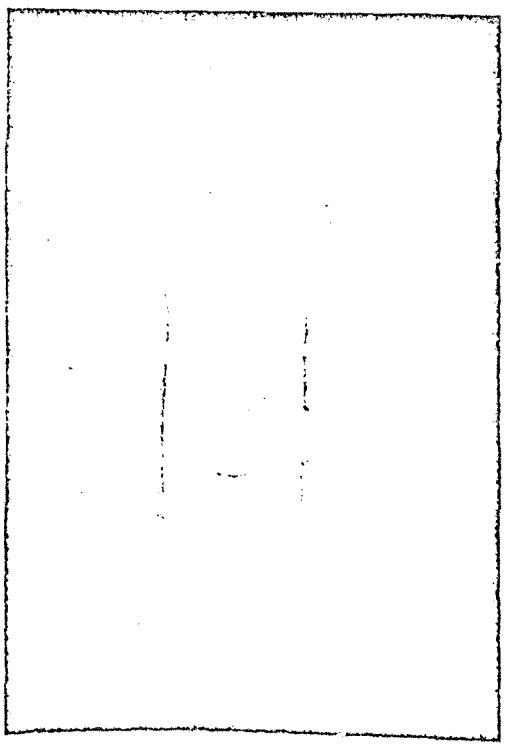

Fig. 16.

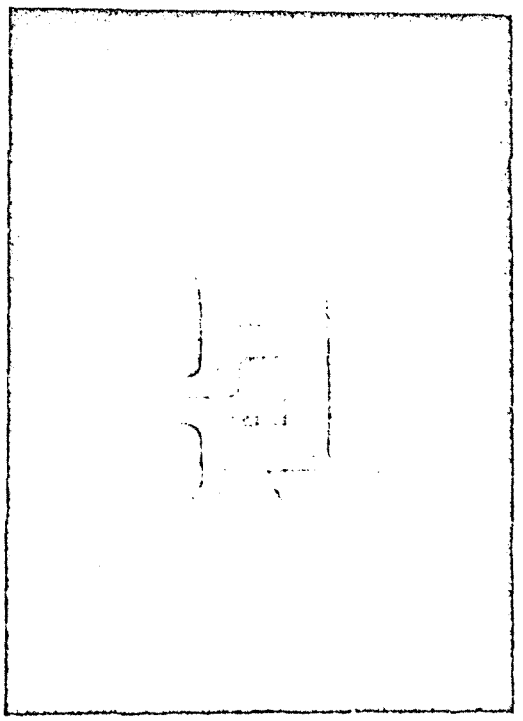

Fig. 17.

anode.

The location of such a spot is determined by a local condition on the surface of the wire. This was clearly shown in several cases where the wire was mounted in such a way that the static charges on the supporting tubes could cause it to rotate through an angle of as much as 180° when the potential was changed. When such a rotation took place the spot or spots would move through the same angle.

Such a blue spot is due to fluorescence caused by bombardment by the electrons from the filament. These electrons are apparently reflected in all directions and cause a blue glow all over the inside wall of the tube except in places where the wall is shielded by some metallic obstacle such as the cathode or anode.

In figs. 16 and 17 can be seen clearly how the electrons are deflected around the cathode giving rise to a "shadow". Somewhat less clearly may be seen the contracted "shadow" of the anode. The electron beams are also strongly deflected by a magnetic field.

When the electron beam or cone strikes the inside of the anode a blue spot is seen on the surface of the metal. This is probably due to a surface layer of oxide or other impurity. If in this case the potential is further increased, then the anode becomes red hot where the blue spot is, but the blue can still be seen clearly.

Frequently bright specks looking like white hot particles are seen in and around the blue spots on the anode.

The spectrum of a bright blue spot on the wall was photographed using a Hilger spectrograph A small slit was used, and the exposure was 24 hours. The spectrum is continuous, showing no lines or bands of any kind. All lenses and prism as well as the tube used in this case were quartz, and the spectrum could therefore be photographed to a considerable distance into the ultra-violet.

The plate was slightly blackened to somewhat below 2700 $\mathring{A}$.

In conclusion I wish to thank Dr. R. A. Millikan for suggesting the problem and for the interest he has taken in the work.

APPENDIX.

APPENDIX.

One of the results of the investigation just described was the establishment of the empirical equation which gives the emission "i" as a function of the applied field "F" viz:

$$i = c\, e^{\frac{-b}{F}}$$

where "A" and "b" are constants for a given set of conditions. As already mentioned this experimental relation was published [1] in Jan.1928 and an independent theoretical derivation by Oppenheimer [2] appeared at the same time and another shortly after by Fowler and Nordheim. [3] Since then the equation has been verified by data from many sources. [1] In the paper referred to above we proposed the equation:

$$i = A(T\ cF)^2\, e^{\frac{-b}{T+cF}}$$

which we thought could be made to express all the available data. It does of course express the facts at both extremes i.e. when either of the variables "T" or "F" is small compared with the other.

Up to that time no experimental data were available for large values of "T" and "F" simultaneously and consequently the nature of "b" remained unknown for this interesting case.

For the cases tested "b" could with sufficient accuracy be considered constant. If this is not the case for the intermediate range, it becomes necessary to determine "b" as a function of "T" and "F" in which case other equations

1) R.A.Millikan and C.C.Lauritsen, Nat.Ac.Sci. 14,45,1928.
2) J.R.Oppenheimer, Phys.Rev. 31,66, 1928.
3) R.H.Fowler and L.Nordheim, Proc.Roy.Soc. 119,173,1928 .

may prove more satisfactory. In view of later experiments it appears likely that "b" is not constant over a wide range, but varies with "T" and "F" in a manner similar to that given by Schottky's relation.

Recently Phorte[4] and de Bruyne[5] the range of "F" is much greater than has been investigated before. His work is of great interest, not only on account of this great range in "F" but because of the extremely consistent measurements. The work seems to have been carried out with the utmost care and constitutes a most beautiful confirmation of Schottky's equation up to field of more than 10^6 volts/cm for all the wires tested with one exception. This wire which was .010 cm tungsten gave normal results with fields of less than $.5 \times 10^6$ volts/cm. Above this value the emission increased much more rapidly with the field at all temperatures from 293 to 1944°.

de Bruyne recognized this as the emission from a very small irregularity on the surface of the wire where the field is much greater than the average field. The only reason why he did not obtain this effect with the other wires is that he did not apply a sufficiently strong field to produce the required irregularity. This is precisely the type of source that we have always used in our work on field emission. With well outgassed tungsten wire it usually requires a field of 4×10^6 volts/cm or more to

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4) W.I.Phorte, Zeit.f.Phys. 49,46,1928.

5) N.A.de Bruyne, Proc. Roy.Soc. 120,423,1928.

produce the irregularity which appears to be an actual break on the surface. It is very essential that the current be limited by a resistance in the circuit or by the power output since otherwise the wire explodes. The shape of the final crater thus obtained depends on the current which is permitted to flow and it is therefore possible to produce points having any desired degree of sharpness within rather wide limits. These points are not always stable and are likely to change or disappear completely at high temperatures.

In a later paper [6] de Bruyne makes a further study of the emission from the point referred to above. He considers only the emission for fields greater than $.5 \times 10^6$ volts/cm average. In this region he assumed that the Schottky equation holds for the emission from the whole surface. He therefore extrapolates the current for lower fields and subtracts the value thus obtained at a given higher field from the measured current. The difference must then be the emission from the irregularity where the field is much greater than the average.

He then plots the log of this emission against $\frac{1}{F}$ and obtains a straight line. For any given temperature this is in perfect agreement with our equation

$$i = A\, e^{-\frac{b}{F}}$$

and is what we have invariably found.

But he goes a step further and attempts to show that the

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6) N.A.de Bruyne, Camb.Phil.Soc. 24,513,1928.

curve obtained in this manner is the same at all temperatures, i.e. that the field emission is completely independent of temperature. This is not in accord with our work. It is true that the temperature dependence is very small and as Millikan and Eyring were the first to show it is almost negligible below 1000°; but that does not produce a more rapid increase at higher temperatures. It seems reasonable from therretical considerations that a temperature dependence exists and all of our data indicates that it does exist and increases with temperature and inversely with the field.

A careful analysis of de Bruyne's data from which he obtains the values plotted on page 519 of his note[6] will show that such a temperature dependence is at least likely. It must be remembered that the currents plotted are differences which in most cases are an extremely small fraction of the total current so that for this reason alone no high order of precision is possible. Then in addition the point from which this small fraction originates is a very uncertain and unstable source.

This is not in any way construed as a criticism of de Bruyne's technique for no one knows better than do we the difficulties involved in working with such a source. We have obtained a large amount of data which is very similar to that shown in fig. 6 of de Bruyne's paper,[6] but we have invariably failed to obtain results which were sufficiently reproducible to warrant treating them as precision measurement. That the same uncertainties exist in de Bruyne's data appears likely from his

fig. 6.

As an example comparing the curves 18 and 19 one certainly gets the impression that some change has taken place between the two sets of readings and it is not likely that curve 18 could be reproduced after 19 had been taken. A smaller change in the opposite direction is probable between 17 and 18. All of the curves are used in the plot of log i $=-\frac{1}{F}$. There is only one at higher temperature (1944°) and here the emission from the point is only from 1 to 10% of the measured current.

This leaves only three curves, viz.,19, 20 and 21 which can reasonably be assumed to have any relation to each other and for these there is indication of an increase with temperature. If we include 18 in the set the increase is still greater, but this is probably not justified as shown above.

The equation

$$i = C\, e^{-\frac{b}{F}}$$

seems to be well verified as does also Schottky's equation for fields less than 10^{6} but it is not possible to decide between the several equations which have been proposed for the intermediate range until much better experimental data is available.