PULLING ELECTRONS OUT OF METALS
BY INTENSE ELECTRICAL FIELDS

California Institute of Technology

PULLING ELECTRONS OUT OF METALS BY INTENSE ELECTRICAL FIELDS

A Thesis
Submitted to the Faculty
in Candidacy for the Degree of
Doctor of Philosophy

Department of Physics

By
Carl Ferdinand Eyring

1923

CONTENTS

ABSTRACT

Pulling Electrons out of Cold Metals by Intense Electrical Fields. Two types of electrodes, placed in a vacuum better than 10^{-6} mm Hg., were used; viz., points and plane with electrode distances from .005 cm to .03 cm, and a fine tungsten wire of .00125 cm diameter and a copper cylinder of 1.625 cm diameter. Making measurements on a micro-photograph of a point--sharp tungsten, dull tungsten, sharp platinum, or dull nickel--and determining the distance between point and plane, the relation between the potential gradient at the end of the point and the potential applied was determined; this relation for the wire surface was determined from the diameters of the wire and cylinder. The maximum available d. c. potential was 12,000 volts which produced a gradient of several million volts per centimeter at the metal surfaces under investigation. The results of the experiments show that electrons are pulled from metals by intense electrical fields, the "field-current" thus produced depending upon the gradient at the surface and not upon the difference of potential between the electrodes. The "field-current" sets in at a "critical" gradient and increases in some cases (untreated tungsten wire and cylinder) over ten millionfold with only a threefold increase in gradient. The

metal points give different "critical" gradients, but these gradients are not thought to be characteristic of the metals but of the surfaces. It is found that the gradient needed to pull electrons out of a metal is controlled by the surface irregularities and especially by surface impurities. The metal surface may be conditioned by heat treatment and by drawing large currents from the surface. The "critical" potential gradient may be increased fourfold by heat treatment, and twofold by the "field-current" conditioning process. The rate of increase of the "field-current" with potential gradient is large when the "critical" gradient is small and vice versa, and large currents drawn from surfaces which have been subjected to intense heat treatment show a fatiguing effect which recovers with time. The "field-current" in general has its origin in a few minute surface spots which presumably locate surface impurities, or surface protrusions, or both. This current is completely independent of temperature between 300°K and 1000° K, but it is slightly greater at 1100° K than at room temperature. The assumption that the "field-current" is made up of conduction electrons, which come out of the surface by virtue of their kinetic energy when the external field has partly annuled the surface attraction, is not tenable in light of the results of this investigation. A new postulate is proposed, viz., that the loosely-bound electrons of the outermost atoms--atoms of impurity of lower electron affinity, or atoms on the tips of protrusions--are pulled away from their atoms by the strong field and then replaced by new electrons, presumably conduction electrons from the interior of the metal. Because of the control which surface conditions have upon "critical" gradients it seems unlikely that any of the results so far given by investigators can be taken as the true characteristic "critical" gradients of the metals, if perchance such characteristic gradients exist. All experimenters obtain gradients of the order of million volts per centimeter; this investigation agrees with others in this particular. A correct surface conditioning technique must be found and agreed upon, then concordant results, which agree not only in order of magnitude but in exact value, may be expected. It is felt that this investigation has added something toward this accomplishment.

PULLING ELECTRONS OUT OF METALS BY INTENSE ELECTRICAL FIELDS

INTRODUCTION.

Among the first experiments to indicate that electrons may be pulled out of metals by intense electrical fields, were those of Earhart[1], Kinsley[2], and Hobbs[3] in which a study was made of the potential required to produce in air sparks of a length comparable with the wave length of sodium light. Their data show that the character of the discharge changes when the electrodes are brought within a certain distance of each other, or, what is equally consistent with the data, when the electric intensity between the plates reaches a certain value--about a million volts per centimeter. Within this region, a plot of the potentials applied and the distances between the electrodes gives a straight line, the slope depending on the kind of metal used. Thus the work of Earhart in 1901 and that of Kinsley and Hobbs in 1905 give evidence that for this type of spark, the carriers are dragged by the electric field out of the metal and not out of the gas.

1. Earhart, Phil. Mag. Vol. 1, p. 147, 1901.
2. Kinsley, Phil. Mag. Vol. 9, p. 692, 1905.
3. Hobbs, Phil. Mag. Vol. 10, p. 617, 1905.

Kinsley worked with exceedingly short sparks, of the order of $3x10^{-7}$ cm in some cases and a corresponding sparking potential of only one volt. Thus a potential gradient of 3.3 million volts per centimeter pulled enough electrons from the metal to produce a spark. He found a linear relation between the spark length and the voltage applied, but the slope of the line representing this relation varied with the treatment of the surface, that is, with the manner in which the surface had been polished and cleaned.

Hobbs, working under the direction of Professor Millikan, used sparking distances of greater length than those used by Kinsley, took extra precautions in cleaning and polishing the surfaces, and allowed a spark to pass but once in the same region of the metal. He found that for distances sufficiently short, so that a linear relation existed between the sparking potential and the distance, the phenomenon was independent of the pressure and nature of the gas, but dependent on the kind of metal used for electrodes. The slopes of the lines--the potential gradients necessary to pull out electrons in sufficient numbers to produce a spark--varied with the metal used, being greatest for Platinum (2 million volts per centimeter) and least for aluminum (1 million volts per centimeter).

In later work Earhart[1] came to the conclusion that the electrode having the lower gradient (that is, requiring the lower gradient to pull out the electrons) controls the discharge irrespective of polarity, and that the carriers of a discharge produced by potential differences less than the least ionizing potential (distance between point and plane five wave-lengths of sodium light and less) are not always negative corpuscles.

Almy[2] gives data which he interprets as being evidence that, so long as the size of the electrode is comparable in size to the length of spark gap, there is a 'minimum potential' below which, no matter what the spark gap, a true spark-discharge does not take place. He concludes that it is not wholly improbable that the strain, which he claims to have eliminated by the use of very small electrodes, may have been sufficient to bring the electrodes used by Earhart and Hobbs into contact when using potentials less than the 'minimum potential'. It seems difficult, however, to see how this explanation can hold in view of the fact that Hobbs found the sparking potential to be a function of the metal used, a phenomenon one would not expect to be explained by assuming that the electrostatic strain is a property of the metal.

1. Earhart, Phil. Mag. Vol. 16, p. 147, 1908.
2. Almy, Phil. Mag. Vol. 16, p. 456, 1908.

G. Hoffman[1], using the interferometer method for measuring very short spark-gaps, the method followed by the previous investigators, and working in air and in vacuum with points and planes at distances of a few wave-lengths of light, found that the sparking potential was proportional to the length of gap and a function of the metal used. This is in agreement with the work of Earhart, Kinsley, and Hobbs, but not in agreement with the work of Almy. Hoffman found that the potential gradient necessary to pull electrons from the metal (produce a spark) was four million volts per centimeter for platinum and ten million volts per centimeter for steel. In a later and a more careful and painstaking investigation, he[2] used a very sensitive electrometer[3] with which he measured currents of the order of 10^{-17} amperes. The electrodes were highly polished and very carefully cleaned. They were not allowed to touch, the length of the spark-gap being determined by used of interference fringes and an electrical scheme in which the sensitive electrometer played an important part. By special precautions a spark was never allowed to pass and, instead of using the sparking potential to determine the critical gradient, he selected as standard the potential

1. Hoffman, Ver. d. D. Phys. Ges. Vol. 12, p. 880, 1910; also Phys. ZS. Vol. 11, p. 961, 1910.
2. Hoffman, ZS. f. Phys. Vol. 4, p. 363, 1921.
3. Hoffman, Phys. ZS. Vol. 13, p. 480 and 1029, 1912; Ann. der Phys. Vol. 42, p. 1196, 1913, and Vol. 52, p. 665, 1917.

for which a current of 1.98×10^{-15} amperes would pass between the electrodes. His results show that for the metals tested, platinum-iridium has the highest critical gradient (4.8×10^6 Volt/cm) and lead the lowest (2.2×10^6 Volt/cm), copper, aluminum and zinc having intermediate values. Critical gradients 50 per cent lower than these were obtained when sufficient care was not taken in the cleaning and polishing process, although to the unaided eye the surfaces appeared clean and smooth.

Hoffman's first observations using electrodes of unlike metals led him to the same conclusions reached by Earhart (1, c. 1908), viz: that the metal having the lower critical gradient controls the discharge irrespective of polarity. A more careful investigation, however, led him to the results that, when a metal of higher critical gradient--gradient determined with like electrodes--is used as the cathode and a metal of lower critical gradient is used as anode, the standard current is reached at a gradient lower than the critical gradient of the cathode, but higher than that of the anode. Thus the critical gradient of this arrangement is higher than he first found it to be, viz: that of the metal of lower gradient, but not as high as one might expect on the assumption that the electrons only serve as carriers. This may be explained on the assumption that positive carriers, charged atoms of the metal of lower critical gradient, play some part in the discharge process.

Lilienfeld[1] has carried out a large number of experiments using as electrode distances 1--12 millimeters, and as electrodes very thin knife-edges, points and planes, a series of points (Spitzenkrone) as cathode and a plane as anode, a pointed cathode and cup-shaped anode, etc. The A. C. voltage applied was of the order of $2\text{-}4\text{x}10^4$ volts and the current which he was able to get between the electrodes was of the order of milli-amperes. The potential gradient[2] at the 'active cathode' surface was of the order of 10^7 volts per centimeter. These experiments differ from those already described because here the distances between the electrodes and the differences of potential are roughly one thousand times greater. Lilienfeld calls the current between the electrodes--it is not a true spark--the auto-electronic current because it is produced by the electric field itself and not by heat, light, or by secondary causes due to ionization. He gives as his reasons for the absence of ionization the fact that he has the best vacuum conditions, that there is no visible glow between the electrodes, that the cathode does not warm up nor change even after 100 hours of operation,

---

[1] Lilienfeld, Ber. d. Math-Phys. Klassa d. Sachsischen Akademie d. Wissenschaften zu Leipzig, Vol. 62, p. 31, 1920; Ver. d. D. Phys. Ges. p. 11, 1921; Phys. ZS. Vol. 20, p. 280-282, 1919; Phys. Zs. Vol. 23, pp. 506-511, 1922.

[2] Schottky ZS. f. Phys. Vol. 14, p. 80, March 1923.

and that the fluoresence on the glass walls, etc., are purely high vacuum phenomena. He finds that the discharge, for given vacuum conditions and a given metal, is a function of the geometrical shape of the electrodes and the distance between them, in other words, a function of the potential gradient at the active surface. However, he finds, that in order to produce 'auto-electronic' currents using finite voltages, he must place the electrodes closer than a given distance, each curvature of active surface having associated with it a particular distance.

For different metals he finds that the one with the longest long-wave-length limit gives off electrons at the lowest voltage, and vice versa. A caesium coated point produces the same sized currents under the action of several hundred volts that the heavier metals produce under the action of as many as 5000 volts. The 'auto-electronic' current he finds to be independent of temperature. On the anode, he observes luminous spots which he calls, "Brennflecke", and for a study of these he uses a concave anode. The spectrum of the "Brennflecke", he finds to be continuous. The cathode, as well as the anode, gives out X-rays, those of the cathode being softer than those of the anode. He thinks that the hardness of the X-rays from the cathode (they pass through the glass tube and a few millimeters of aluminum) is too great to be attributed to the acceleration of the electrons by the field at the active surface, but thinks that they might be caused by the shifting of electrons from outer orbits to inner ones, the shifting being due to a distortion by the strong field of the outer electron orbits.

Professor Millikan, continuing the work of Hobbs, but increasing the distance between the spheres to one millimeter and placing the spark gap in a vacuum, found the sparking potential to be a function of the sphere surfaces; the magnitude of the potential being controlled by the nature of the surface cleaning and polishing and by the number of times the spark was passed. Because of their irregularity the data were not published, and Professor Millikan became convinced that a more careful study of the problem should be undertaken. The investigation was continued off and on for as many as ten years, the general conclusion being that in a vacuum so high that the gas plays no further part in the discharge, the potential gradient at a metal surface necessary to obtain a discharge is exceedingly variable even for the same metal surface. He and Mr. Shackelford[1] published a note in which they state that with clean untreated surfaces--two crossed tungsten wires, size 18, placed a few millimeters apart--they were able to get a first leak, as measured on a tilted

---

[1] Millikan and Shackelford, Physical Review, Vol. 15, p. 239, Mar. 1920.

electroscope, using a gradient at the surface of from 100,000 to 500,000 volts per centimeter. When heated to red heat and then cooled, these same surfaces gave a first leak at from 400,000 to 700,000 volts per centimeter. On heating to 2700°K the first leak was pushed up to 4,300,000 volts per centimeter and the first spark up to six million volts per centimeter.

The present investigation is a further continuation of this attempt to see just how far surface conditions control the field strength needed to pull electrons out of cold metals. Since there was available a maximum D. C. potential of only 12,000 volts, and since we wished to make the distance between the electrodes as large as possible, it became necessary to design the apparatus in a manner such that the field intensity at the surface to be investigated would be very large because of the small radius of curvature of the surface. Hence two types of electrodes have been used in these experiments, viz., point and plane, and a fine wire at the axis of a cylinder, the point being the cathode in the first case and the wire playing this role in the second. It seems natural to divide the investigation into two parts, using the type of electrode as the criterion of division.

POINT AND PLANE

I. Field Strength at End of Point.

The points are shaped, as nearly as possible, in the form of hyperboloids of revolution, thus making possible the accurate calculation of the field strength at the end of a point.

Let the axis of symmetry of the hyperboloid be the X-axis and the plane which contains the Y and Z axes be the metallic plane, then with the point placed at the correct distance from the plane and with a difference of potential between the electrodes we shall have a system of hyperboloids of revolution and an orthogonal system of half ellipses representing the equipotential surfaces and lines of force respectively.

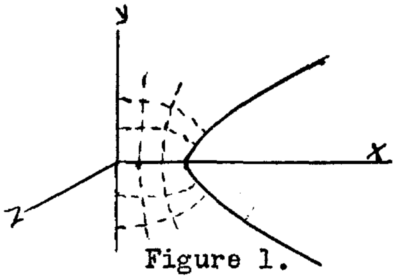


Figure 1.

For the free space between the point and the plane we have the equation of Laplace,

$$\Delta\phi = 0 \tag{1}$$

Which in generalized coordinates becomes,

$$\Delta\phi = \frac{1}{\mathcal{U}\mathcal{V}\mathcal{W}}\left\{\frac{\partial}{\partial u}\left(\frac{\mathcal{V}\mathcal{W}}{\mathcal{U}}\frac{\partial\phi}{\partial u}\right)+\frac{\partial}{\partial v}\left(\frac{\mathcal{W}\mathcal{U}}{\mathcal{V}}\frac{\partial\phi}{\partial v}\right)+\frac{\partial}{\partial w}\left(\frac{\mathcal{U}\mathcal{V}}{\mathcal{W}}\frac{\partial\phi}{\partial w}\right)\right\}=0 \tag{2}$$

where an element of length is given by,

$$dl^2 = \mathcal{U}^2du^2 + \mathcal{V}^2dv^2 + \mathcal{W}^2dw^2$$

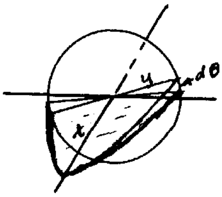
Because of the nature of the equipotential surfaces and the lines of force it is desirable to change to hyperbolic coordinates. This may be accomplished by use of these transformations,

$$x = av\sqrt{u^2+1} \;;\; y = au\sqrt{1-v^2} \;;\; z = y \tag{4}$$

We may write for Cartesian coordinates, symmetrical with respect to the X-axis, the following,

$$dl^2 = dx^2 + dy^2 + y^2d\theta^2 \tag{5}$$

Making use of the transformation equations (4),



$$dx = a\sqrt{u^2+1}\,dv + \frac{avu}{\sqrt{u^2+1}}\,du,$$

$$dy = a\sqrt{1-v^2}\,du - \frac{auv}{\sqrt{1-v^2}}\,dv.$$

Now from (5)

$$dl^2 = dx^2 + dy^2 + y^2d\theta^2$$

$$= \frac{a^2(a^2-v^2+1)}{1-v^2}\,dv^2 + \frac{a^2(a^2-v^2+1)du^2}{u^2+1} + y^2dw^2;$$

since the system is symmetrical with respect to the X-axis and the new coordinate w is therefore the angle θ.

But from (3)

$$d\ell^2 = U^2 du^2 + V^2 dv^2 + W^2 dw^2.$$

Hence,

$$U = a\sqrt{\frac{u^2-v^2+1}{u^2+1}}\,;\quad V = a\sqrt{\frac{u^2-v^2+1}{1-v^2}}\,;\quad W = au\sqrt{1-v^2}. \tag{6}$$

Since the system is symmetrical with respect to the X-axis, and since the hyperboloids of revolution are equipotential surfaces we have at once,

$$\frac{\partial \phi}{\partial w} = \frac{\partial \phi}{\partial u} = 0,$$

and thus,

$$\frac{\partial}{\partial v}\,\frac{UW}{V}\,\frac{\partial \phi}{\partial v} = 0.$$

At once using the values given above for U, V and W we have,

$$\frac{\partial}{\partial v}\left(\frac{\dfrac{a^2u\sqrt{1-v^2}\cdot\sqrt{u^2-v^2+1}}{u^2+1}}{a\sqrt{\dfrac{u^2-v^2+1}{1-v^2}}}\cdot\frac{\partial \phi}{\partial v}\right) = 0,$$

and

$$\frac{\partial}{\partial v}\left(\frac{du\,(1-v^2)}{\sqrt{u^2+1}}\cdot\frac{\partial\phi}{\partial v}\right)=0.$$

Solving,

$$(1-v^2)\left(\frac{\partial\phi}{\partial v}\right)=A,$$

and

$$\frac{\partial\phi}{\partial v}=A\left(\frac{1}{1-v^2}\right).$$

Hence

$$\phi=A\int\frac{dv}{1-v^2}$$

Integrating,

$$\phi=\frac{A}{2}\log\frac{1+v}{1-v}+B.$$

On the surface of the point we put,

$V = V_0$ and $\phi = \phi_0$. Since the plate is kept at zero potential or very near it, we write,

$\phi = 0$ at the plate where $V = 0$, hence at once it follows that $B = 0$, and for A we solve and get,

$$A=\frac{2\phi_0}{\log\frac{1+V_0}{1-V_0}}$$

Then having determined the constants we may write,

$$\phi=\phi_0\,\frac{\log\left[\frac{1+v}{1-v}\right]}{\log\left[\frac{1+V_0}{1-V_0}\right]}.$$

The electric force is now obtained from the relation,

$$E = -\frac{\partial \phi}{\partial S_v} = -\frac{1}{\gamma}\frac{\partial \phi}{\partial v}.$$

This may be put in the form,

$$E = -\frac{1}{a}\sqrt{\frac{1-v^2}{a^2-v^2+1}} \cdot \frac{A}{1-v^2} = -\frac{A}{a}\frac{1}{\sqrt{(u^2-v^2+1)(1-v^2)}}.$$

Now at the surface of the point we have $v = v_o$ and at the end of the point $u = o$, hence for the potential gradient at the end of the point we have the relation,

$$E_o = -\frac{A}{a}\frac{1}{1-v^2} = \frac{2\phi_o}{a\log\frac{1+v_o}{1-v_o}} \cdot \frac{1}{1-v_o^2}. \qquad (7)$$

The problem now is to determine the values of a and v_o for the different points. Assuming a point to be a true hyperboloid of revolution and properly placed with respect to the plane so as to be an equipotential surface in the type of field considered, then eliminating u between the transformation equations (4), we have the hyperbola,

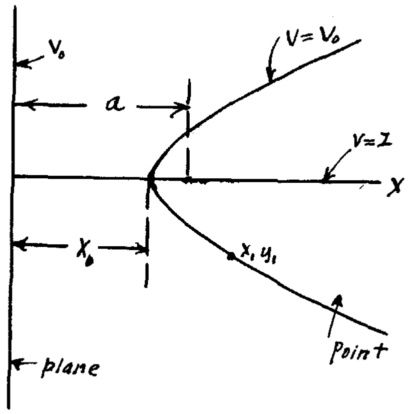


Figure 2.

$$\frac{x^2}{a^2v^2} - \frac{y^2}{a^2(1-v^2)} = 1, \qquad (8)$$

which when revolved about the X-axis gives an equipotential surface. For the metal point we have this hyperbola,

$$\frac{X^2}{a^2 V_0^2} - \frac{y^2}{a^2(1-V_0^2)} = 1 \qquad (9)$$

Call the distance between the end of the point and the plane X_0, Figure 2, then from equation (9) we have

$$\frac{X_0^2}{a^2 V_0^2} = 1 \qquad \text{and } X_0 = aV_0 \text{ and } a = \frac{X_0}{V_0} \qquad (10)$$

Thus a is determined in terms of x_0 and v_0. Obviously x_0 can be measured by use of a good micrometer microscope. The coordinates of a given point (x_1, y_1,) located on the edge of the image of the metallic point as given by a microphotograph (Figure 3, page 18), can be measured and at once v_0 can be determined from the equation,

$$V_0^{2\;\text{sim}} = \frac{X_1^2 - X_0^2}{X_1^2 + y_1^2 - X_0^2} \qquad (11)$$

provided, of course, x_0 and x_1 are reduced to the same scale. This is necessary since x_0 is a direct measurement and x_1 is a measurement obtained from a photograph of an enlarged image of the point.

Actually the point is not a true hyperboloid of revolution because of construction difficulties. Hence, within a limited range, there is no one value of x_0 which should be used more than another; that is, no distance

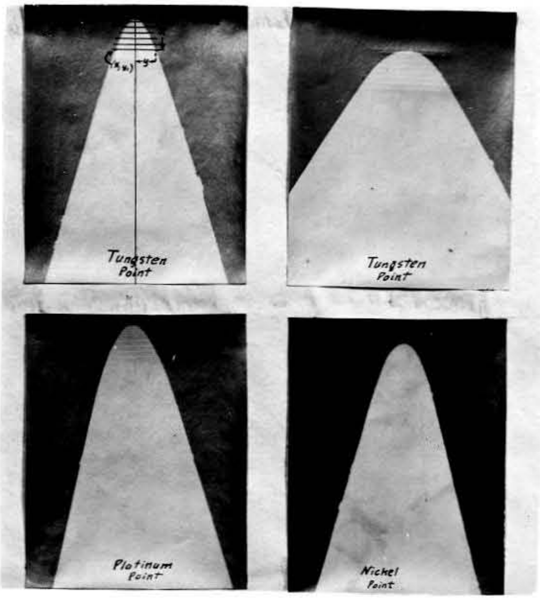


Figure 3

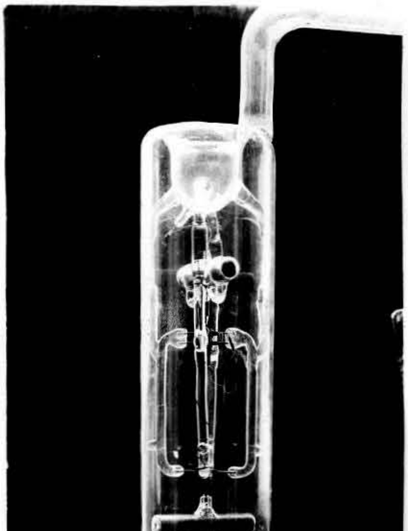


Figure 4

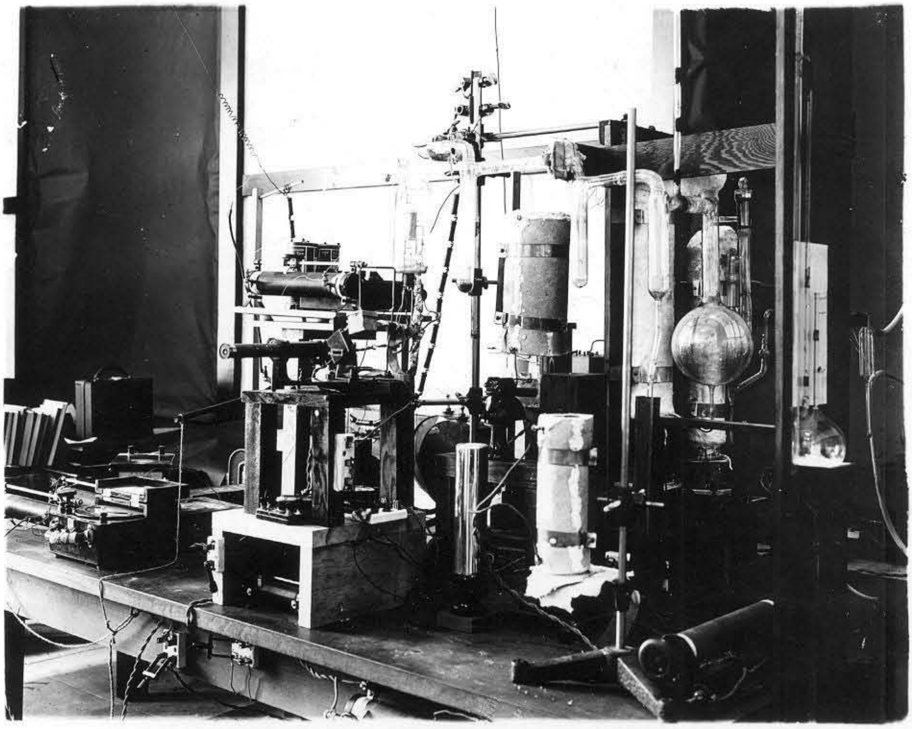
between the point and the plane will give exactly the field described above. However, if for a given value of x_0, v_0 be calculated from the coordinates of a number of points on the curve, and if the values of v_0 thus calculated be the same or nearly so, then a good value of v_0 is assured. This leads to an approximation method to be used in this investigation. The value of x_0 is varied, values of (x_1, y_1) are found from the curve (photograph of the point), and for each particular value of x_0 an average value of v_0 is calculated--a greater weight being given to the portion of the curve near the vertex. Finally the values of a are arrived at. For a rather wide range in the values of x_0, the values of v_0 for a given x_0 are surprisingly constant for calculations made using the part of the curve (photograph) near the end of the point. From this it follows that although theoretically each distance between point and plane should have a slightly different shaped point, yet practically the point serves well for a considerable variation of this distance.

II. Apparatus and Method of Procedure.

Four metal points--sharp tungsten, blunt tungsten, sharp platinum, and sharp nickel--were made as nearly as possible in the form of hyperboloids of revolution, polished and cleaned. Then using a projection lantern with a microscope attachment, micro-photographs were made of each point by allowing its enlarged image to fall upon sensitized photographic paper. These photographs are shown in Figure 3, page 18. The points were then mounted in the glass tube, Figure 4, page 18. The glass structure in which the points are sealed also contains an enclosed soft iron rod. The structure is sealed to a small shaft which is free to turn, and it is easy, by the use of an outside magnet, to bring each point in its turn before a small polished stationary tungsten disc, the plane. By means of a sleeve the other end of the shaft is fitted into a threaded journal. A second glass enclosed iron rod is sealed to the screw part of the journal and thus by the use of an outside magnet a given point may be moved forward and back simply by making the screw turn. Concentric with the tungsten disc is a thoriated tungsten filament which is the source of thermions in the process of heating the points and plane by electronic bombardment.

The vacuum is produced by two mercury condensation pumps placed in series. A liquid air trap is used to freeze out the mercury vapor, Figure 5, page 21.

The tube was baked during exhaust at 350° C for eight hours. The tungsten disc and points were heated to white heat, approximately 2200° K, a number of times by electronic bombardment. The platinum point was heated to



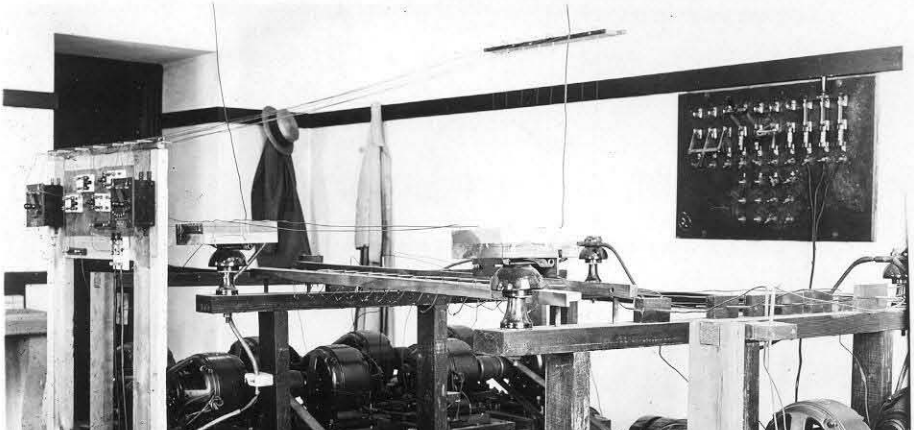


Figure 5

approximately 1900° K. By mistake the nickel point was heated to a temperature somewhat above its melting point, 1725° K, and it thereby became a very blunt point. When data was being taken the pressure was always as low or lower than 10^{-6} mm. of mercury, the lowest pressure which could be estimated on the McLeod gauge.

Direct current generators are the source of high electromotive force, (Figure 5, page 21). A Max Kohl electrostatic voltmeter V is used to measure the difference of potential between the point and the plane and a tilted electroscope is used to measure the first small electrical leak between the electrodes. The arrangement of apparatus is shown diagrammatically in Figure 6, page 23. Care is taken properly to insulate and shield the wire which leads from the tungsten disc (plane) to the electroscope.

The method of taking data is as follows. After the precautions of pumping and baking as described above, a desired point is brought before the disc, the electrode distance adjusted, and this distance measured by a micrometer-microscope. The insulation of the electroscope including the wire to the tungsten disc is tested and the calibration of the electroscope checked by an auxiliary battery not shown in the figure. Now with the leaf of the electroscope and the

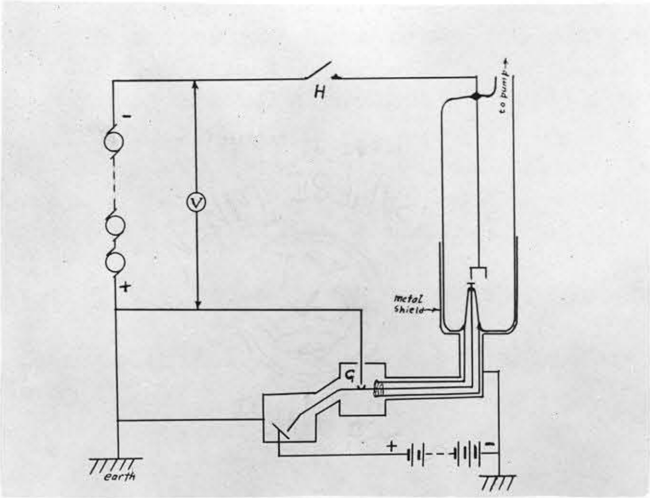


Figure 6

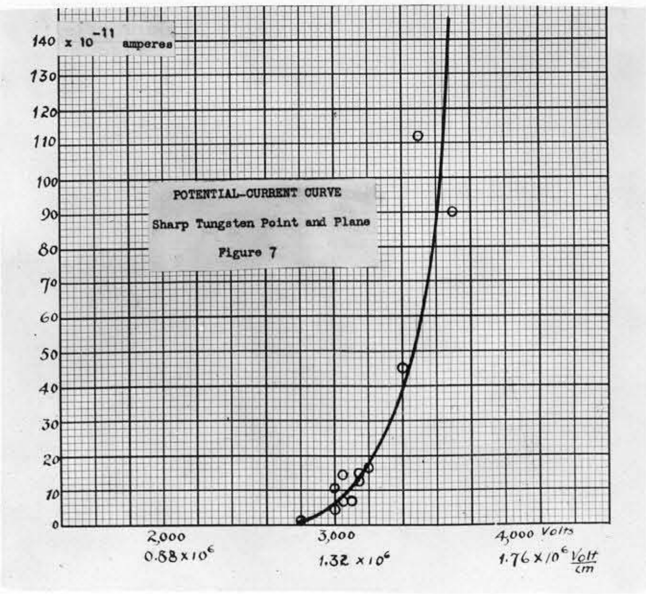


Figure 7

plane grounded by the switch G, the switch H is closed and a potential applied to the point. When all is steady the switch G is opened and if a proper negative potential has been applied the movement of the electroscope leaf will indicate a charging up of the plate negatively which means a passage of electrons from the point to the plane. That this leak is not on the inside of the glass is shown by the fact that with a reversal of this potential no current (positive or negative) is detected.

III. Results.

Potential-Current Curve. With the tilted electroscope adjusted to give 50 scale divisions for 24 volts (one scale division per second = 1.8×10^{-11} amperes, the capacity of the electroscope and connection being 34 electrostatic units), and with a distance between the sharp tungsten point and the plane of 0.0075 cm., the following potential-current data were obtained in the order given.

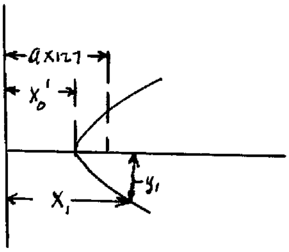
Table I.

Potential	Current
3400 volts	45.0 x 10^{-11} amp.
3200	16.1
3100	7.2
3150	12.9
4100	405.0
3500	112.0
3000	10.6
3500	112.0
3050	14.3
(Next day, otherwise conditions the same).	
3700	90.0
3150	15.8
3050	6.9
3000	4.5
2800	1.5

These data and their graphical representation (Figure 7, page 23) show that the current begins at a "critical" voltage or gradient and then increases very rapidly with an increase in potential.

<u>Potential Gradient at Points.</u> As explained on page 17, in order to determine the value of the potential gradient at the end of the points it is necessary to determine the parameters a, x_0, and v_0. By use of equation (10) a is at once determined from x_0 and v_0. By a simple measurement with a micrometer microscope the distance between point and plane, x_0, is determined. By use of vernier calipers the x and y coordinates of points lying near the vertex of the hyperbola--the photograph of the metallic point--are measured. These values, averages from two photographs of the sharp tungsten point, are as follows, x_0' being x_0 reduced to magnified scale.

X	Y
x_0' + .10 cm.	.240 cm.
.20	.308
.30	.387
.50	.497
.70	.594
.90	.689
1.10	.775



The magnification is 127 times hence, for the particular electrode distance, $x_0 = .0121$ cm, $x_0' = 127 \cdot x_0 = 1.54$ cm.

By use of the above data and equation (11) we have the following.

X	Y	V_0
1.64	.240	.921
1.74	.308	.935
1.84	.387	.934
2.04	.497	.938

2.24	.594	.940
2.44	.689	.940
2.64	.775	.941

Average v_0 = .935

a = .0129 cm.

ϕ_0 = 2950 volts.

$$E_0 = \frac{2\,\phi}{a \log \dfrac{1 + v_0}{1 - v_0}} \cdot \frac{1}{1 - v_0^2}$$

$$= 1{,}070{,}000 \text{ Volt / cm.}$$

This illustrates how the potential gradient, E_0, is determined for the different shaped points, and for different electrode distances.

In the data given below, Table II, x_0 is the distance between the point and plane, Φ is the potential which is necessary to produce a "field-current" of 2.3×10^{-12} amperes, and E_0 is the corresponding "critical" potential gradient at the end of the point. These results were taken after the preliminary heating, and presumably, therefore, they are observations for given surface conditions.

Table II.

Sharp Tungsten Point

X_o	ϕ_o	E_o
.0057 cm.	2100 volts	1.04 x 10^6 Volt/cm.
.0075	2750	1.146
.0121	2950	1.068
.0113	2950	1.082
.0146	3250	1.088
.0330	4350	1.076
.0558	5550	1.206
.0983	6500	1.102
		1.102 x 10^6 Av.

Dull Tungsten Point

X_o	ϕ_o	E_o
.0077 cm.	4050 Volts	.800 x 10^6 Volt/cm.
.0057	3000	.76
.0102	5000	.83
.0198	7100	.83

Sharp Platinum Point

X_o	ϕ_o	E_o
.0065 cm.	6300 Volts	2.38 x 10^6 Volt/cm.
.0048	5600	2.46

Very Dull Nickel Point[1]

X_o	ϕ_o	E_o
.0247 cm.	7500 Volts	0.45 x 10^6 Volt/cm.
.0165	6200	0.48

---

[1] The nickel point had been melted during the heat treatment so it became necessary to estimate its shape by use of the micrometer-microscope, rather than by use of its photograph.

These data show very clearly that the pulling of the electrons out of a metal is not determined by the voltage applied, but by the potential gradient which, for a given treatment of the metal surface, remains constant.

The seeming discrepancy between the "critical" gradients for tungsten and the possibility of the values given here being characteristic gradients of the metals will be discussed later. As we shall see, the surface conditions are, to a great extent, the controlling factors in determining the "critical" gradients.

Pulling Positive Metal Ions From Points. When a positive potential is applied to the points, the data given below, Table III, seem to indicate that, in the case of the sharp tungsten point, positive tungsten atoms are the carriers of the current; while in the case of the sharp platinum point both positive platinum atoms and electrons make up the carriers; and in the case of the dull tungsten point only electrons carry the current. These conclusions are based on the fact that for the sharp points the first electrical leaks, as measured before and after the reversal of polarity, do not appear at the same "critical" gradients, while under the same conditions the first electrical leaks for the blunt tungsten point appear at the same gradient; and further because, when a positive potential is applied to the points, the gradient at the plane, in the case of the sharp tungsten point, is too small to pull out electrons, while for the blunt tungsten point this gradient is sufficiently large. Furthermore, since there is no modification of the blunt point when a "field-current" is obtained with the point acting as anode, it seems correct to conclude that electrons pulled from the plate are the only carriers used in this case. The sharp platinum point when used as anode is modified by the current and the potential gradient at the plane under these conditions is sufficiently great to pull out electrons, hence the conclusion for this case that both positive and negative particles carry the current.

Table III.

	Before reversal of Polarity (Point charged negatively)	Positive potential applied to point		After reversal (Point charged negatively)
	E_o (at point)	E_o(at point)	E_o(at plane)	E_o (at point)
Sharp tungsten	1.10×10^6V/cm.	1.70×10^6V/cm.	$.22 \times 10^6$V/cm.	1.34×10^6V/cm.
Dull tungsten	.81	1.42	.73	.84
Sharp platinum	2.42	2.34	.93	1.39

The varied behavior of the points is largely due to the differences in geometrical form.

Effect of Impurities. The values of the gradients given in Table II, were obtained after a preliminary heating. It now seemed advisable to try the effect of further heating. In every case it was found that the heating of a point to very dull redness made it easier to pull out the electrons, and heating it to a yellow whiteness made it more difficult to pull them out. The surprising thing is that this process is more or less reversible, that is, roughly speaking a point can be made "hard" or "soft" at will. The most probable explanation is as follows: Thorium is evaporated from the thoriated filament used as the source of thermions and a small amount of this is deposited on the point being bombarded only to be reevaporated when the point is at white heat, but retained on the surface when the point is heated only to dull redness. Placing the point near the hot filament when no bombarding potential is applied will sometimes, but not always, make the point "soft".

Table IV.

	Heating to white heat. E_0	Heating to dull red. E_0
Sharp tungsten point	1.04×10^6 V/cm.	$.64 \times 10^6$ V/cm.
	2.00	.90
	1.67	
Blunt tungsten point	1.38	.57
	1.04	
Sharp platinum point	2.46	.95
	3.16[1]	.67

---

[1] The platinum point was melted in a further attempt to make the point "hard".

WIRE AND CYLINDER

I. Field Strength at Surface of Wire.

The wire is located at the axis of the cylinder, hence when a difference of potential is applied, lines of force will extend radially from the wire to the cylinder and be located in planes normal to the axis of the wire. For the free space between the wire and the cylinder we have the equation of Laplace, viz.,

$$\Delta \phi = 0 \qquad (1)$$

Choosing the axis of z as the axis of symmetry this equation becomes in Cartesian coordinates

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0,$$

the general solution of which is,

$$\Phi = A \log p + B, \text{ where } p^2 = x^2 + y^2, \qquad (2)$$

and where p is the distance from the axis of symmetry, and A and B are arbitrary constants to be determined by the boundary conditions. Suppose the potential at the surface of the wire is Φ_1 and at the surface of the cylinder Φ_2 , then if R and r represent the radius of the cylinder and the wire respectively, we have

$$\Phi_2 = A \log R + B$$

$$\Phi_1 = A \log r + B$$

Solving for A and B and substituting in equation (2) we have,

$$\phi = \frac{1}{\log \frac{R}{r}} \left((\phi_2 - \phi_1) \log p + \phi_1 \log R - \phi_2 \log r \right)$$

Now remembering that $E = - \frac{\partial \phi}{\partial r}$ we have,

$$E = - \frac{1}{\log \frac{R}{r}} (\phi_2 - \phi_1) \frac{1}{p}$$

At the surface of the wire we write $p = r$ and as the cylinder is always very close to zero potential we place $\Phi_2 = 0$ and write,

$$E = \left(\frac{\phi}{\log \frac{R}{r}} \right) \left(\frac{1}{r} \right) \tag{3}$$

as the equation to be used in calculating the potential gradient at the surface of the wire. By measuring the diameters of the wire and cylinder it is at once possible to calculate the relation between the voltage applied and the gradient at the surface of the wire.

The diameter of the wire was measured by two methods. The first method involved the use of an excellent Zeiss oil-immersion compound microscope. The diameter of the wire as seen in the microscope was compared with a standard scale placed at the focal plane of the microscope eyepiece. A standard scale, graduated to tenths of millimeters was then viewed through the microscope, and the divisions compared with the scale in the eyepiece. It was thus possible to calculate the diameter of the wire. The second method was simply the calculation of the diameter from the mass and density of a given length of the wire. The mass was determined by weighing the wire on a specially designed torsion balance built by the author. On this balance one can estimate to hundredths of milligrams and obtain results which agree among themselves to at least .02 of a milligram.

The results of the two methods are as follows:

Microscope Method.

(a) Tungsten direct from spool.

Size of wire-------- 8.10 av. div. eyepiece scale,
Size of 1/10 mm.----66.5 av. div. eyepiece scale,
Diameter of wire---- .00122 cm.

(b) Tungsten wire which had been heated to 2900^{o}K.

Size of wire-------- 8.07 av. div. eyepiece scale,
Diameter of wire---- .00121 cm.

Weight Method.

Weight of 50 cm. of tungsten wire------- 1.13 mg.
Diameter of wire, using 19 as density[1]-- .00123 cm.

According to Langmuir[1] the weighing method has been found to be the most accurate means of obtaining the diameter of small wires. As determined by the high-powered microscope, the diameter of the wire does not vary more than one percent. There are very small irregularities, however; these will be considered and discussed later (P.76). In view of the above data and these considerations, the diameter may be taken as equal to .00123 cm. and may be considered correct to about one percent. The diameter of the cylinder is 1.625 cm. Hence from equation (3) we have,

$$E = \frac{\phi}{\log \frac{1.625}{.00123} \cdot \frac{.00123}{2}} = 228\,\phi,$$

a simple relation between the gradient and the potential.

---

[1] Langmuir, Physical Review, Vol. 7, No. 3, p. 302, Mar. 1916.

II. Apparatus and Method of Procedure.

The apparatus used in this part of the investigation consists of a Pyrex glass tube, Figure 8, in which is placed a fine tungsten wire W and a copper cylinder C. The wire is kept taut by a four-gram iron weight I, and is adjusted so as to be in the axis of the cylinder. Two leads are connected to either end of the fine wire and then brought through a seal in the upper part of the tube. It is thus possible to send a current through the tungsten wire and thereby heat it to any desired temperature. When the wire is heated to temperatures over 1100°K the iron weight is lifted by means of an electromagnet, E. With this arrangement one may keep the wire taut at low temperatures and yet be insured against its breakage at high temperatures.

The cylinder is supported by a large tungsten wire which is sealed in the post P. This post has a glass sleeve which is used, when the cylinder is heated to bright redness in the process of denuding it of gases, as a precaution against a deposit of copper which might form on the post and thus spoil its insulating properties. An earthed guard ring is placed around the post P so that, in case a charge should be conducted on the inside of the glass, none of it will reach the cylinder. The large tungsten wire passes through the seal

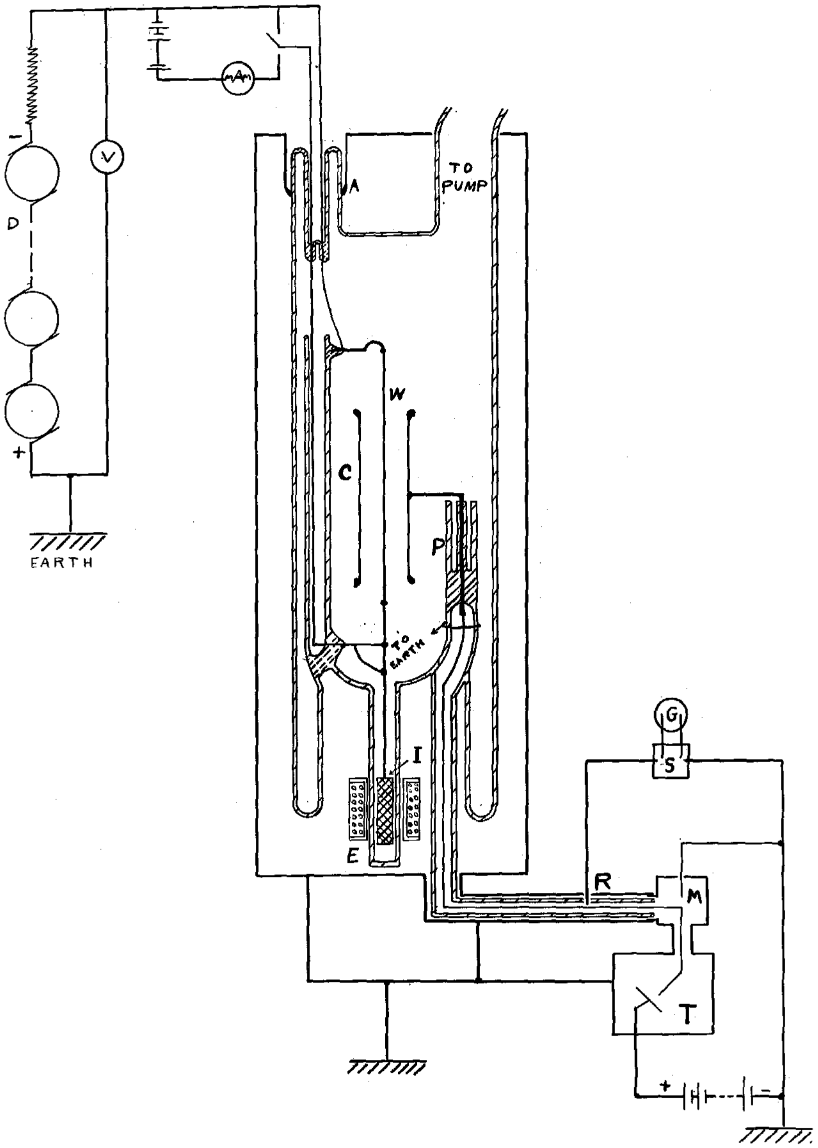


Figure 8

in the post to the outside of the tube where it is joined to a copper wire which leads to the tilted electroscope. A small glass tube is sealed to the main tube in such a manner as to enclose this conductor which is then electrically shielded by covering the glass with earthed tin-foil.

An electric heater surrounds the main glass tube. The metal cylinder on which the heating coils are wound is grounded and thus the heater serves as an electric shield for the tube. A grounded guard ring is placed at A, Figure 8, to keep the outside of the tube from becoming charged when a high potential is applied.

Direct current generators are used as the source of high potential, the maximum voltage available being 12000 volts. In series with the generators is placed a million ohms resistance to protect the apparatus should a short circuit be established between the wire and the cylinder. A Max Kohl electrostatic voltmeter V, calibrated in place, is used to measure the potential applied between the wire and the cylinder. A tilted electroscope T and a galvanometer G provided with a variable shunt are used to measure the "field-current" between the wire and the cylinder. The wire to the galvanometer is disconnected at R when the tilted electroscope is being used.

The pumping apparatus is the same as that described in the point and plane experiment, except for a charcoal trap which is now added. To insure the best of vacua the tube and charcoal were baked during exhaust by means of electric furnaces for not fewer than 4 hours, and in a number of cases for as many as 18 hours. Four to six hours of proper baking[1] seems to be as effective as the eighteen-hour treatment. Under the long treatment the process used is as follows. The tube and charcoal trap are heated to 420° C, for one hour, the pumps working at maximum speed all the while. The temperature is then allowed to fall to 370° C and kept there for ten hours. At the close of this heating, with the temperature still at 370° C the McLeod gauge should show no measurable pressure (pressure less than 10^{-5} mm of mercury). The heat is now turned off the charcoal, but the tube is heated at 230° C for 10 hours. At the close of this period liquid air is placed on the charcoal trap. Liquid air has been on the mercury trap since the first half hour of heating, when it was supposed that a large portion of the water vapor had been pumped out. This is a precaution against collecting too much water vapor in the mercury trap. Liquid air is now kept on both traps both day and night, and if for any reason the liquid air is left off, at least part of the baking process is repeated.

---

1. High Vacuum by Dushman, p. 157-159.

The shorter process, which seems just as effective, is to bake for one hour at 420° C, then for three to five hours at 370° C. By this time, if the pumps are working properly, and the apparatus is perfectly tight, the McLeod gauge will show no measurable pressure with both charcoal and tube at 370° C.

After this type of baking a pressure less than 10^{-6} mm of mercury was obtained. The tube would stand over night, liquid air on both traps, and then show no measurable pressure on the McLeod gauge.

At the proper time in the investigation the cylinder was heated to cherry red for from eight to twelve minutes by electronic bombardment. The bombarding potential was 2,000 volts and the bombarding current 100 milliamperes. The filament used as the source of thermions is stretched in a series of zigzags around and within half a centimeter of the cylinder. This part of the apparatus is not shown in the figure.

The method of taking data is essentially the same as in the point and plane experiment. In addition to the tilted electroscope, a galvanometer is added which will measure currents from 3×10^{-8} amperes to milliamperes by the proper use of an Aryton shunt. The current used to heat the wire is measured by means of a good multimeter (Rawson Electrical Instrument Co.) or a Weston milliammeter. If the wire is to be heated at the same time voltages are applied to it, then the apparatus used to furnish and measure the heating current is placed on an insulated stand. Using data published by Langmuir[1], the temperature of the wire is obtained from the value of the current in the wire and its diameter.

Observations were taken on three specimens of thoriated tungsten wire. These pieces were from the same spool and, as explained above, had a diameter of .00123 cm. When a new wire was introduced the tube was opened up, the wire supplied, and the tube sealed up again. This method was rather inconvenient, but the process insured the possibility of the best obtainable vacuum. When observations were being made the pressure was always less than 10^{-6} mm. Hg.

III. Results.

In recording the data obtained from a study of the three specimens of thoriated tungsten wire, it seems best not to attempt to put down all the data taken, nor to try to maintain their chronological order, but to record representative data in a natural sequence which has grown out of a consideration of the data as a whole. Since the three wires are of the same material, the same diameter, and show the same characteristics, data will be selected irrespective of the wire used. The wires will be numbered I, II, III, the number indicating the order in which they were investigated.

---

1. Langmuir, Physical Review, Vol. 7, p. 302, Mar. 1916.

The Rapid Rise of "field-current" with Increasing Potential Gradient and the Reversibility of the Process. The data recorded below are for Wire I which had received no heat treatment, except that which was necessary, in baking out the tube, but which had been conditioned, as explained below, by a large "field-current" of 0.42 milliamperes.

Φ is the potential between the wire and the cylinder, E is the potential gradient at the surface of the wire, and I is the current between the wire and the cylinder--the electrons pulled from the tungsten wire--which we shall call the "field-current".

Table V.

Φ	E	I[1]	$\mathrm{Log}_{10}(\mathrm{I}\mathrm{x}10^{12})$
1810 Volts	$.41\mathrm{x}10^{6}$ Volt/cm.	$9.7\mathrm{x}10^{-12}$ Amp.	0.99
2500	.57	$3.0\mathrm{x}10^{-8}$	4.48
2750	.63	$1.5\mathrm{x}10^{-7}$	5.18
3000	.68	$7.5\mathrm{x}10^{-7}$	5.87
3500	.80	$4.8\mathrm{x}10^{-6}$	6.68
3900	.89	$2.7\mathrm{x}10^{-5}$	7.43
4200	.96	$6.9\mathrm{x}10^{-5}$	7.84
4600	1.05	$2.1\mathrm{x}10^{-4}$	8.32
5000	1.14	$3.9\mathrm{x}10^{-4}$	8.59
4400	1.00	$9.0\mathrm{x}10^{-5}$	7.95
3900	.89	$2.4\mathrm{x}10^{-5}$	7.38
3600	.82	$8.7\mathrm{x}10^{-6}$	6.94
3000	.68	$8.7\mathrm{x}10^{-7}$	5.94
2500	.57	$3.0\mathrm{x}10^{-8}$	4.48
1750	.40	$9.7\mathrm{x}10^{-12}$	0.99

---

[1] The first and last readings of the current were taken on the tilted electroscope, the other reading on the galvanometer. The electroscope was adjusted to give 50 div. for 3 volts; the capacity of electroscope and leads was 73 electrostatic units. Two divisions per second equals $9.7\mathrm{x}10^{-12}$ Amperes.

Table V. (Cont'd)

Trial 2.

Φ	E	I	$\text{Log}_{10}(\text{I}\times10^{12})$
1750 Volts	$.40\text{x}10^{6}$ Volt/cm.	$9.7\text{x}10^{-12}$ Amp.	0.99
2500	.57	$3.0\text{x}10^{-8}$	4.48
2700	.62	$2.0\text{x}10^{-7}$	5.29
2900	.66	$6.2\text{x}10^{-7}$	5.79
3300	.70	$1.5\text{x}10^{-6}$	6.18
3400	.78	$3.9\text{x}10^{-6}$	6.59
3700	.84	$1.4\text{x}10^{-5}$	7.15
3800	.88	$1.8\text{x}10^{-5}$	7.26
4000	.91	$3.6\text{x}10^{-5}$	7.56
4220	.96	$6.0\text{x}10^{-5}$	7.78
4400	1.00	$8.1\text{x}10^{-5}$	7.91
4750	1.08	$2.1\text{x}10^{-4}$	8.32
4950	1.13	$3.6\text{x}10^{-4}$	8.56
4650	1.06	$1.8\text{x}10^{-4}$	8.26
4400	1.00	$8.7\text{x}10^{-5}$	7.94
4000	.91	$3.3\text{x}10^{-5}$	7.52
3700	.84	$1.4\text{x}10^{-5}$	7.15
3400	.78	$4.5\text{x}10^{-6}$	6.65
3050	.70	$1.1\text{x}10^{-6}$	6.04
2750	.63	$2.1\text{x}10^{-7}$	5.32
2400	.55	$3.0\text{x}10^{-8}$	4.32
1800	.41	$9.7\text{x}10^{-12}$	0.99

The graphical representation of the data of Table V is shown in Figure 9, page 44. These data and their graphical representation show that for a clean "field-current-conditioned" tungsten surface, but not heat-conditioned or treated, the "field-current" increases more than ten millionfold with a threefold increase of potential gradient, that is, from $.40\text{x}10^{6}$ to $1.13\text{x}10^{6}$ Volt/cm. And these data further show that for "field-currents" lower than the current which conditioned the surface the process is quite accurately reversible.

Conditioning the surface By Means of "Field-current". "Field-currents" drawn from the surface for the first time, or for the first time after some heat treatment such as a long baking out of the tube, the heating of the cylinder to cherry-red heat, the heating of the wire by means of a current, etc., generally produced a permanent effect upon the surface making it more difficult to pull out the electrons. This is shown by the data in Table VI below. The change or conditioning of the surface is also dependent on the maximum current drawn from the surface, (Table VII), and is not dependent, except to a very slight extent, on how long a time the current is drawn from the surface (Table VIII). When once conditioned, and then not subjected to further conditioning by current or by heat, the surface seems to be constant, because, as explained above, if the maximum conditioning "field-current" is not exceeded, the current run is reversible, (Table V). The exception to this reversible action is the case of surfaces subjected to intense heat treatment, as explained in connection with the data represented in Figure 11.

The "field-current"--voltage data in Table VI are for Wire II. They are the first observations on this wire, therefore, the currents are the first to be taken from the tungsten surface.

Table VI.

First, or Conditioning Run.

Φ	E	I	$\text{Log}_{10}(I\times10^{12})$
850 Volts	$.19\times10^{6}$ Volt/cm.	9.7×10^{-12} Amp.	0.99
1500	.34	1.5×10^{-8}	4.18
1650	.38	3.0×10^{-8}	4.48
1900	.43	2.1×10^{-7}	5.32
2250	.51	2.1×10^{-6}	6.32
2500	.57	1.2×10^{-5}	7.08
2700	.62	2.4×10^{-5}	7.38
2800	.64	3.9×10^{-5}	7.59
3000	.68	6.6×10^{-5}	7.82
3500	.80	1.2×10^{-4}	8.08
4000	.91	3.3×10^{-4}	8.52
4400	1.00	5.4×10^{-4}	8.73
4000	.91	2.1×10^{-4}	8.32
3700	.84	8.4×10^{-5}	7.92
3500	.80	3.3×10^{-5}	7.52
3150	.72	1.1×10^{-5}	7.03
3000	.68	6.3×10^{-6}	6.80
2600	.59	6.6×10^{-7}	5.82
2300	.52	7.5×10^{-8}	4.88
1500	.34	9.7×10^{-12}	0.99

Second Run.

2200	.50	3.0×10^{-8}	4.48
2450	.56	2.9×10^{-7}	5.46
2900	.66	3.6×10^{-6}	6.56
3100	.71	1.0×10^{-5}	7.00
3350	.76	1.8×10^{-5}	7.23
3500	.80	4.1×10^{-5}	7.61
3700	.84	8.7×10^{-5}	7.94
3900	.89	1.5×10^{-4}	8.18
4200	.96	3.3×10^{-4}	8.52
4000	.91	2.1×10^{-4}	8.32
3800	.87	1.1×10^{-4}	8.06
3500	.80	3.9×10^{-5}	7.59
3100	.71	9.9×10^{-6}	6.99
2900	.66	3.0×10^{-6}	6.48
2500	.57	4.5×10^{-7}	5.65
2300	.52	1.1×10^{-7}	5.02
1530	.35	9.7×10^{-12}	0.99

The graphical representation of the data of Table VI is shown in Figure 10, page 44.

Table VII.

The Conditioning of the Surface Dependent on Maximum "Field-current" used in the process.

Wire II.

Φ	I	Φ	I
1060 Volts	$9.7x10^{-12}$ Amperes	3500 Volts	$1.4x10^{-5}$ Amperes
1750	$3.0x10^{-7}$	4000	$6.6x10^{-5}$
2000	$2.4x10^{-6}$	4550	$2.7x10^{-4}$
1750	$2.1x10^{-7}$	4000	$4.5x10^{-5}$
2000	$1.4x10^{-6}$	3500	$6.9x10^{-6}$
2500	$1.5x10^{-5}$	3000	$5.7x10^{-7}$
2000	$5.7x10^{-7}$	2500	$3.0x10^{-8}$
1750	$6.0x10^{-8}$	3000	$5.7x10^{-7}$
2000	$3.9x10^{-7}$	3500	$6.6x10^{-6}$
2500	$6.6x10^{-6}$	4000	$4.8x10^{-5}$
2000	$3.0x10^{-7}$	4550	$2.1x10^{-4}$
1750	$6.0x10^{-8}$	5000	$5.4x10^{-4}$
2000	$3.0x10^{-7}$	4550	$1.8x10^{-4}$
2500	$5.7x10^{-6}$	4000	$3.9x10^{-5}$
2000	$3.3x10^{-7}$	3500	$5.1x10^{-6}$
1750	$6.0x10^{-8}$	3000	$3.9x10^{-7}$
2000	$3.2x10^{7}$	3500	$4.8x10^{-6}$
2500	$5.7x10^{-6}$	4000	$3.6x10^{-5}$
3000	$9.0x10^{-6}$	4550	$1.8x10^{-4}$
2500	$7.8x10^{-7}$	5000	$4.5x10^{-4}$
2000	$5.0x10^{-9}$	5500	$1.1x10^{-3}$
2500	$7.8x10^{-7}$	5000	$3.6x10^{-4}$
3000	$6.3x10^{-6}$	4550	$1.5x10^{-4}$
2500	$4.5x10^{-7}$	4000	$2.4x10^{-5}$
2000	$9.0x10^{-9}$	3500	$3.9x10^{-6}$
2500	$5.4x10^{-7}$	3000	$2.1x10^{-7}$
3000	$6.0x10^{-6}$	2550	$3.0x10^{-8}$
3500	$2.1x10^{-5}$	3000	$2.3x10^{-7}$
3000	$2.1x10^{-6}$	3500	$3.6x10^{-6}$
2500	$1.5x10^{-7}$	4000	$2.7x10^{-5}$
2200	$3.0x10^{-8}$	4550	$1.5x10^{-4}$
2500	$1.8x10^{-9}$	5000	$3.9x10^{-4}$
3000	$2.4x10^{-6}$	5200	$6.0x10^{-4}$
3500	$2.1x10^{-5}$	5000	$3.9x10^{-4}$
4000	$8.4x10^{-5}$	4550	$1.5x10^{-4}$
3500	$1.5x10^{-5}$	4000	$2.6x10^{-5}$
3000	$1.5x10^{-6}$	3500	$3.5x10^{-6}$
2500	$4.5x10^{-8}$	3000	$3.0x10^{-7}$
3000	$1.5x10^{-6}$	2550	$3.0x10^{-8}$
		1740	$9.7x10^{-12}$

These data show that the wire can be conditioned for any desired range of currents, but that with increasing range there is a modification of the surface which lowers the "field-current" for a given gradient. Furthermore, they show that the conditioning is not due to any particular sized "field-current", but is simply due to the maximum current arrived at. Yet all sizes of "field-currents" are not equally effective in the conditioning process.

Wire II, having been conditioned by the runs given in Table VI, was now tested for the effect of an hour's operation with a "field-current" of 0.2 of a milliampere.

Table VIII.

Time	Φ	E	I
	1530 Volts	$.35 \times 10^6$ V/cm.	9.7×10^{-12} Amperes
	2250	.51	6.0×10^{-8}
	2500	.57	3.6×10^{-7}
	2750	.63	1.5×10^{-6}
	3000	.68	6.6×10^{-6}
	3500	.80	3.3×10^{-5}
	3800	.87	1.1×10^{-4}
0 min.	4000	.91	2.1×10^{-4}
10	4000	.91	2.1×10^{-4}
20	3950	.90	1.5×10^{-4}
30	3950	.90	1.5×10^{-4}
40	3950	.90	1.5×10^{-4}
50	3920	.89	1.4×10^{-4}
60	3900	.89	1.2×10^{-4}
	3760	.86	7.5×10^{-5}
	3550	.81	3.9×10^{-5}
	3250	.74	9.6×10^{-6}
	3000	.68	3.0×10^{-6}
	2550	.58	3.3×10^{-7}
	2430	.55	9.0×10^{-8}
	1550	.35	9.7×10^{-12}

The long period of operation does not change the "critical" potential gradient for it is $.35 \times 10^6$ V/cm both before and after the operation, yet as may be seen from Tables VI and VII, the "field-current" conditioning process changed the critical gradient from .19 to $.34 \times 10^6$ in one case, and from .24 to $.40 \times 10^6$ Volt/cm in the other case. The continued operation seems to decrease the absolute values of the large "field-currents" about 25 per cent.

A gradient of 1.7×10^6 V/cm applied to a surface which had been subjected to extreme heat treatment produced what seems to be a breaking or rupture of the surface, for as will be seen from the data of Table IX, the "field-current" increased slowly until this gradient was reached and then suddenly the current increased a thousandfold. Two definite spots, presumably the region of rupture, appeared for the first time and gave off nearly the whole of the current, for only two spots could be seen on the cylinder. Not only was the current for a given gradient increased, but the critical gradient was changed from 0.74 to 0.48×10^6 V/cm. This observation was made on Wire III; no similar effect was observed on the other wires.

Table IX.

Φ	E	I
5100 Volts	1.16×10^{6} V/cm.	3.0×10^{-8} Amp.
5450	1.24	9.0×10^{-8}
6100	1.39	1.5×10^{-7}
6700	1.53	2.0×10^{-7}
7100	1.62	2.6×10^{-7}
7800	1.78	1.8×10^{-4}

Conditioning the Surface by Heat Treatment. The effect produced by heating the wire is so tied up with how the impurities on the surface respond to different temperatures, that it seems best to divide the results of heat treatment into a number of parts, using the temperature range as the criterion of division.

First, consider temperatures below 1200° K. Long baking of the tube at 400° C reduced the "critical" potential gradient of a "field-current-conditioned" wire, this in spite of the fact that no change ever took place when the tube stood over night, or for a number of days, provided the vacuum was maintained during this time. This is clearly shown by the data of Table X.

Table X.

	"Critical" Gradient[1]		Maximum temp.
Wire	Before baking	After baking	of baking.
I	0.48×10^{6} V/cm.	0.37×10^{6} V/cm.	360° C.
I	0.40	0.38	420° C.
II	0.40	0.34	420° C.
III	No data.		

---

[1] In this and the following tables, "critical" gradient is the potential gradient needed to produce a "field-current" of 9.7×10^{-12} amperes.

Heating Wire II at 900°--1100° K greatly reduced the "critical" gradient of a "current-conditioned" surface. The phenomenon is roughly reversible, but becomes less pronounced with continued treatment as may be seen from a consideration of the data of Table XI.

Table XI.

Conditioning "field-current"	"Critical" Gradient Before heating,	After heating.	Temper-ature.	Total time of heating after conditioning.
0.70 milli-amp.	0.41×10^6 V/cm.	0.34×10^6 V/cm.	900°K.	5 min.
		0.32	900	10
0.24	0.41	0.38	900	15
		0.40	900	30
0.24	0.41	0.41	900	10
0.24	0.41	0.24	1100	5
1.05	0.40	0.27	1100	15
		0.24	1100	30
		0.22	1100	45
		0.21	1100	60
		0.22	1100	90
0.045	0.40	0.27	1100	15
		0.24	1100	35

Wire I did not show this effect at 900°-1100° K, but as this phenomenon is no doubt caused by an impurity on the wire surface, it is not surprising to find this wire lacking in this particular. However, as may be seen from the data of Table XII, heating did make the critical gradient lower, but this change took place at a temperature higher than 1100° K and was only temporary. Wire III, though not studied in the same manner as that illustrated in Table XI, does show similar tendencies as may be seen from the data of Table XIII below.

Second, consider the effect on the wire of heating the cylinder to cherry-red, 1400° K approximately. The wires were not in the same condition when this treatment was made. Wire I had a "critical" gradient of 0.48×10^6 V/cm. which had been produced by a conditioning current of .84 milliamperes. After heating the cylinder this gradient was changed to 0.34×10^6 V/cm. In the case of Wire II, on the other hand, the gradient had been reduced by heating at 1100° K as explained above, and had a value of 0.24×10^6 V/cm. This was changed to 0.36×10^6 V/cm by heating the cylinder. After the third wire was placed in the tube, the procedure was somewhat changed. The tube was baked out, and without testing for the "critical" gradient the cylinder was heated. The "critical" gradient was then tested and the value 0.39×10^6 V/cm found.

Third, consider the effect of temperatures above 1100° K. Wire I had been current-conditioned at a "critical" gradient of 0.51×10^6 V/cm before the heating. The effect of heating is as follows.

Table XII.

Temp.	Total time of heating at the particular temp.	Resulting "critical" gradient.
1500° K	1 min.	0.50×10^6 V/cm.
2000	1	0.33
	6	0.22
	16	0.63
2300	1	0.65
	6	0.66
	16	0.67
2500[1]	2	0.67
	6	0.67

At the beginning of the high temperature treatment, Wire II had a "critical" gradient of 0.32×10^6 V/cm. which was found to remain constant at a temperature of 1100° K due to previous treatment. The results of the high temperature treatment are given in Table XIII.

Table XIII.

Temp.	Total time of heating at the particular temp.	Resulting "critical" gradient.
2000°[2] K	2 min.	0.90×10^6 V/cm.
	7	0.87
1500	5	0.66
	15	0.67
2000	2	0.80
2500[3]	2	0.75

---

[1] By accident in later work the wire was burned out and hence no higher temperatures were reached.

[2] When I returned the next morning after taking this reading I found the apparatus had developed a crack and that air had filled the tube. After baking the tube, heating the cylinder to cherry-red heat, and "current-conditioning" the surface a "critical" gradient of 0.57×10^6 V/cm was obtained. Heating the wire for 15 minutes at 1100° K changed this value to 0.46×10^6. The heat treatment was then continued.

[3] The wire broke before higher temperatures were reached.

Wire III had not been treated except by the baking of the tube at 420° C and the heating of the cylinder to cherry-red heat. The effect of temperature treatment is as follows:

Table XIV.

Temperature.	Total time of heating at the particular temp.	Resulting "critical" gradient.
1100° K	10 min.	0.39×10^{6} V/cm.
1300	10	0.39
1500	10	0.31
	25	0.26
	40	0.29
1700[1]	20	0.27
1900	10	0.57
	25	0.46
	40	0.34
	55	0.61
1800	15	0.46
	30	0.42
	45	0.68
2300[2]	10	0.74
2800	1	0.47
2900	1	(wire broke when weight was applied.)

---

1. This temperature and those lower are about 100-200° K too high, if one is to judge by the color of the wire. In the other two wires 1100°K produced a just visible red color, while in this case no color was visible till 1300°K (as determined by the current and diameter) was reached. The heating above the temperature recorded as 1700 K produced a change in the wire (not in diameter for this wire was later checked with a microscope) so that the current measurements gave temperatures in agreement with the color of the wire. Langmuir (l.c. March 1916) speaks of conditioning the wires for one minute at a temperature of about 1500° K. This treatment he says causes the evolution of an amount of gas (mostly carbon monoxide) which measured at atmospheric pressure is usually 3 to 6 times the volume of the filament. There is also a simultaneous change in the filament whereby its cold resistance is lowered 15 to 20 per cent, and the temperature coefficient of its resistance <u>increased</u> by a like amount.
2. After this reading a current-voltage run was made as shown in

Large Currents Drawn From Surfaces Subjected to Intense Heat Treatment Show Fatiguing Effects which Recover With Time. The higher the "critical" gradient, which corresponds to a higher temperature in the heat treatment, the greater is this effect. This is shown to be true from a consideration of the data given below, Tables XV and XVI, and also from Figure 11, page 58, which is a graphical representation of the data of Tables VI, XV, and XVI, the data of Table VI, which is for a "current-conditioned" wire, being added simply for comparison purposes.

Table XV.

Potential	Gradient	Current	$\text{Log}_{10}(I\times10^{12})$
2200[1] Volts	0.50×10^{6} V/cm.	9.7×10^{-12} Amp.	0.99
3500	0.80	9.0×10^{-8}	4.95
4000	0.91	4.5×10^{-7}	5.65
4600	1.05	3.6×10^{-6}	6.56
5000	1.14	6.6×10^{-6}	6.82
5500	1.25	1.9×10^{-5}	7.28
6000	1.37	5.1×10^{-5}	7.71
5700	1.30	2.7×10^{-5}	7.43
5150	1.18	7.5×10^{-6}	6.88
4700	1.07	2.1×10^{-6}	6.32
4200	0.96	5.1×10^{-7}	5.71
3800	0.87	9.0×10^{-8}	4.95
3500	0.80	3.0×10^{-8}	4.48

Table IX. There was no doubt a breaking or rupture of the surface at one particular spot on the wire, for all of a sudden two bright spots appeared on the wall of the cylinder and the current increased a thousandfold. After several current-voltage runs, the "critical" gradient was steady at 0.48×10^{6}V/cm. The heating process was then continued.

[1] The current for this voltage was measured on the tilted electroscope, the other currents on the galvanometer. This voltage gives the "critical-gradient".

Table XV (Xont'd)

Potential	Gradient	Current	Log$_{10}$(Ix10^{12})
2290[1] Volts	0.52 V/cm.	$9.7\text{x}10^{-12}$ Amp.	0.99
After 15 min. 3500	0.80	$4.5\text{x}10^{-8}$	4.65
4200	0.96	$7.5\text{x}10^{-7}$	5.88
4500	1.02	$1.9\text{x}10^{-6}$	6.28
5100	1.16	$9.9\text{x}10^{-6}$	6.99
5600	1.28	$3.0\text{x}10^{-5}$	7.48
6100	1.39	$7.2\text{x}10^{-5}$	7.86
5500	1.25	$2.1\text{x}10^{-5}$	7.32
5000	1.14	$6.3\text{x}10^{-6}$	6.80
4500	1.02	$1.5\text{x}10^{-6}$	6.18
4000	0.91	$3.0\text{x}10^{-8}$	4.48
2250[1]	0.51	$9.7\text{x}10^{-12}$	0.99

Table XVI.

Potential	Gradient	Current	Log$_{10}$(Ix10^{12})
2800[1] Volts	$0.64\text{x}10^{6}$V/cm.	$9.7\text{x}10^{-12}$ Amp.	0.99
4750	1.08	$1.5\text{x}10^{-8}$	4.18
5500	1.25	$4.5\text{x}10^{-8}$	4.65
6150	1.40	$1.5\text{x}10^{-7}$	5.18
6600	1.50	$2.1\text{x}10^{-7}$	5.32
7100	1.62	$3.0\text{x}10^{-7}$	5.48
7800	1.78	$6.0\text{x}10^{-7}$	5.79
8700	1.98	$1.2\text{x}10^{-6}$	6.08
7800	1.78	$5.1\text{x}10^{-7}$	5.71
7000	1.60	$1.7\text{x}10^{-7}$	5.23
6500	1.48	$6.0\text{x}10^{-8}$	4.79

---

[1] The currents for these voltages were measured on the tilted electroscope, the other currents on the galvanometer. These voltages give the "critical-gradients".

Table XVI (Cont'd).

Potential	Gradient	Current	$\log_{10}(I\times10^{12})$
5950 Volts	1.35 V/cm.	1.5×10^{-8} Amp.	4.18
3300[1]	0.75	9.7×10^{-12}	0.99

After one hour the first leak had changed from 3300 volts back to 2800 volts. The fatiguing effect had disappeared after an hour's rest. After 15 hours of rest the results given below were obtained.

2720[1]	0.62	9.7×10^{-12}	0.99
4200	0.93	6.0×10^{-9}	3.79
4700	1.07	1.5×10^{-8}	4.18
5150	1.17	4.5×10^{-8}	4.65
5700	1.30	9.0×10^{-8}	4.95
6200	1.41	1.5×10^{-7}	5.18
6700	1.53	2.7×10^{-7}	5.43
7100	1.62	3.9×10^{-7}	5.59
7700	1.75	4.5×10^{-7}	5.65
8700	1.98	1.1×10^{-6}	6.04
7800	1.78	4.5×10^{-7}	5.65
7100	1.62	3.0×10^{-7}	5.48
6500	1.48	1.2×10^{-7}	5.08
6000	1.37	6.0×10^{-8}	4.79
5500	1.25	2.4×10^{-8}	4.38
3400[1]	0.78	9.7×10^{-12}	0.99

After one hour.

2810[1]	0.64	9.7×10^{-12}	0.99

---

[1] "Critical" potential.

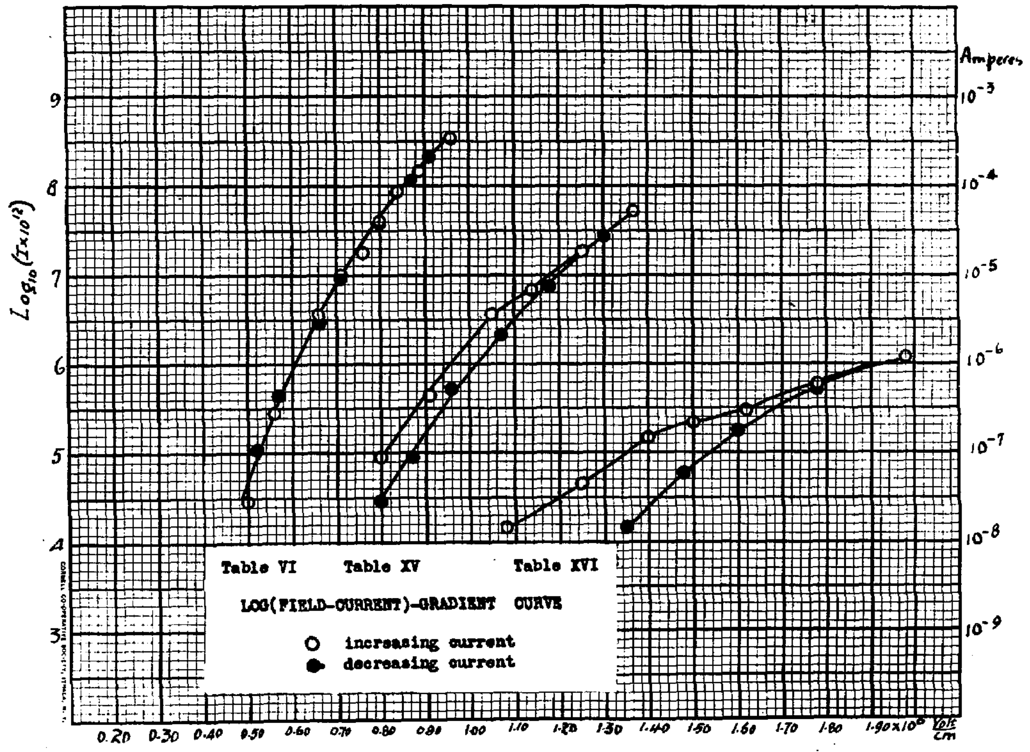


Table VI
Table XV
Table XVI
LOG(FIELD-CURRENT)-GRADIENT CURVE
○ increasing current
● decreasing current
$Log_{10}(I \times 10^{12})$
3
4
5
6
7
8
9
Amperes
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90×10^{6} $\frac{Volt}{cm}$

Figure 11

Slope of "Field-current"--Gradient Curve a Function of "Critical" Gradient. The rate of increase of the "field-current" with the potential gradient is large when the "critical" potential gradient is small and vice versa. This is clearly shown in Figure 11, page 58, a graphical representation of the data of Tables VI, XV, and XVI.

The "Field-currents" in General have their Origin in a Few Minute Surface Spots. For small currents, lower than 10^{-6} amperes, and for corresponding voltages lower than 4000 volts, the tube remains perfectly black as viewed in a darkened room. (Currents lower than these may produce a luminous effect if the voltage is sufficiently high.) For larger currents luminous spots begin to appear on the surface of the cylinder, and fluorescent spots appear on the glass wall directly out from the top of the cylinder. The spots are no doubt due to streams of electrons shot out from small regions on the surface of the wire.

The patches of light on the cylinder are reddish-grey in color, and as viewed through a direct-vision prism seem to have a continuous spectrum. However, this point should be tested more carefully in an apparatus designed for this purpose.

As the field current increases the spots become brighter and new spots appear. Some of the spots are fixed in position and, for a given current, constant in luminosity; others are slightly changeable in position, and before a steady current state is reached, rather changeable in intensity, and even when the current appears steady, there is some variation in these points. Sometimes in the "current-conditioning" process, very brilliant spots spring into existence. This is well illustrated by the action of Wire II. An irregularity was noticed in the "field-current" and on looking into the tube a new spot was seen on the cylinder near its center. The spot was changeable in intensity but fixed in position. Its intensity slowly decreased and its luminosity became more steady. Thereafter, the current ceased to fluctuate. Another interesting case is that observed in the study of Wire III. The wire had been heat-conditioned and was giving off very small "field-currents" considering the magnitude of the voltages applied, and there was only slight traces of luminosity. The next small increase of voltage (see Table IX, p.50) produced a thousandfold increase in current. Two luminous spots had sprung into existence. They furnished practically all the "field-current" which was rather unsteady. These spots were fixed in position, but very changeable in intensity. The luminosity slowly decreased with continuous operation and the current settled into a more or less steady state.

The "Critical" Gradients and the "Field-currents" are Completely Independent of Temperature Between 300°K and 1000°K.

Only data for the temperature of 900° K will be recorded, although the effect of lower temperatures was investigated. Wires I and II were studied for this effect; the different "critical" gradients for the same wire are due to the previous conditioning process. The results are recorded in Tables XVII and XVIII.

Table XVII.

	"Critical" Gradient[1]	
Wire	300°K	900°K
I	0.415×10^6 V/cm.	0.408×10^6 V/cm.
	0.409	0.410
	0.417	0.408
	0.417	0.410
	0.413	0.410
		0.413
I	0.670	0.672
	0.672	0.670
	0.670	0.655
	0.655	
II	0.730	0.730
	0.741	0.736
	0.741	0.741
	0.741	

---

1. The potential gradient needed to produce a "field-current" of 9.7×10^{-12} amperes.

Table XVIII.

Wire	Potential difference	Potential gradient	"Field-current"			
			900°K	300°K	900°K	300°K
II	1730 V.	0.39×10^{6} V/cm.	9.7×10^{-12} A.	9.7×10^{-12} A.	9.7×10^{-12} A.	9.7×10^{-12} A.
	2500	0.57	9.0×10^{-8}	9.0×10^{-8}	9.0×10^{-8}	9.0×10^{-8}
	3000	0.68	1.9×10^{-6}	1.8×10^{-6}	1.8×10^{-6}	1.8×10^{-6}
	3500	0.80	6.0×10^{-6}	6.0×10^{-6}	5.7×10^{-6}	5.7×10^{-6}
	4000	0.91	4.4×10^{-5}	3.9×10^{-5}	4.2×10^{-5}	4.1×10^{-5}
	4550	1.04	2.4×10^{-4}	2.3×10^{-4}	2.3×10^{-4}	2.3×10^{-4}
	4000	0.91	4.2×10^{-5}	4.2×10^{-5}	4.4×10^{-5}	4.4×10^{-5}
	3500	0.80	7.2×10^{-6}	7.1×10^{-6}	7.2×10^{-6}	7.2×10^{-6}
	3000	0.68	6.9×10^{-7}	6.3×10^{-7}	7.2×10^{-7}	6.9×10^{-7}
	2500	0.57	3.0×10^{-8}	3.0×10^{-8}	3.0×10^{-8}	3.0×10^{-8}
	1810	0.41	9.7×10^{-12}	9.7×10^{-12}	9.7×10^{-12}	9.7×10^{-12}
I	8450	1.92	9.0×10^{-7}	9.0×10^{-7}		

The "Critical" Gradients and "Field-currents" with *Wire at 1100°K.* (The wire is a just-visible-red color.) The extent of the lowering of the "critical" gradient with this temperature depends on the magnitude of the "critical" gradient at room temperature, zero effect being observed for very low gradients and a large effect for higher gradients, Table XIX; the magnitudes of the "critical" gradients at room temperature, of course, being the result of past treatment of the surface. At 1100°K the "field-currents" are not only larger for feeble currents, but for currents of the order of a tenth of a milliampere, Table XX.

Table XIX.

Wire	"Critical" Gradient 300°K	 1100° K
II	$0.212\text{x}10^{6}$ V/cm	$0.212\text{x}10^{6}$ V/cm
	0.212	0.212
	0.214	0.213
	0.216	0.214
	0.215	
	0.317	0.310
	0.317	0.310
	0.315	
	0.450	0.358
	0.456	0.360
	0.458	0.364
	0.800	0.560
	0.800	0.561
	0.792	0.560
I	0.402	0.315
	0.402	0.319
	0.399	0.322
	0.400	0.335
	0.399	0.335
	0.399	

Table XX.

Wire	Potential difference	Potential gradient	 300°K	"Field-current" 1100°K	 300°K
I	2600 Volts	$0.59\text{x}10^{6}$V/cm.	$1.2\text{x}10^{-8}$ amp.	$1.5\text{x}10^{-8}$amp.	$1.5\text{x}10^{-8}$amp.
	3050	0.70	$1.2\text{x}10^{-7}$	$1.4\text{x}10^{-7}$	$1.2\text{x}10^{-7}$
	3500	0.80	$6.0\text{x}10^{-7}$	$7.5\text{x}10^{-7}$	$6.0\text{x}10^{-7}$
	4000	0.91	$4.5\text{x}10^{-6}$	$5.4\text{x}10^{-6}$	$4.4\text{x}10^{-6}$
	4400	1.00	$2.1\text{x}10^{-5}$	$2.4\text{x}10^{-5}$	$2.1\text{x}10^{-5}$
	4750	1.08	$5.4\text{x}10^{-5}$	$5.9\text{x}10^{-5}$	$5.4\text{x}10^{-5}$
	5000	1.14	$1.0\text{x}10^{-4}$	$1.1\text{x}10^{-4}$	$1.0\text{x}10^{-4}$
	4800	1.09	$6.3\text{x}10^{-5}$	$6.9\text{x}10^{-5}$	$6.0\text{x}10^{-5}$
	4200	0.96	$1.2\text{x}10^{-5}$	$1.5\text{x}10^{-5}$	$1.2\text{x}10^{-5}$
	3750	0.85	$2.1\text{x}10^{-6}$	$2.7\text{x}10^{-6}$	$2.1\text{x}10^{-6}$
	3200	0.73	$2.4\text{x}10^{-7}$	$3.6\text{x}10^{-7}$	$2.4\text{x}10^{-7}$
	3000	0.68	$9.0\text{x}10^{-8}$	$1.5\text{x}10^{-7}$	$1.0\text{x}10^{-7}$

Presumably the field, with increasing strength, penetrates farther and farther into the molecular or crystalline interstices of the surface, thus catching more and more of the free electrons which now come up into this region by virtue of the added kinetic energy associated with this temperature (1100°K). This would account for the appearance at 1100° K of an increase of the "field-current" for the large as well as the small values of current.

DISCUSSION OF RESULTS.

The "field-current" is certainly produced by intense electrical fields at the surface of the metal. The assumption that positive gaseous ions strike against the surface with sufficient energy to free the necessary electron carriers for the "field-current" does not seem tenable for the following reasons. First the vacuum is of the order of 10^{-6} mm. of mercury and less, hence only a very few ions could be present. Second, there is no visible radiation from the wire. Third, the current is found to be a function of the potential gradient and not the potential difference (see Table II). Fourth, the "field-current" comes from very small regions of the wire and one can hardly see why the ions, which would have gained the greatest part of their energy and velocity by the time they reached the immediate neighborhood of the surface, could in the remaining very short distance be deflected to particular regions. This view, of course, is based on the assumption that the field between the cylinder and wire is exactly the same, up to the immediate neighborhood of the surface, as if the wire had a perfectly smooth and cylindrical surface, and that within a distance of say one fiftieth of the diameter of the wire the field is distorted due to microscopic and ultra-microscopic irregularities. Fifth, it has been shown[1] that positive ions impinging upon a cathode with volocities corresponding to a fall through a potential difference of up to 2000 volts (possibly larger voltages), are unable to liberate electrons from the surface of a cathode. In view of the fact that for certain cases (Table VI) currents as large as 10^{-7} amperes were obtained with differences of potential less than 2000 volts, one seems perfectly justified in concluding that the electrons are not helped out of the metal by the action of positive ions.

Furthermore, it is not likely that any considerable portion of the electrons which make up the "field-currents" are photo-electrons, because, if one assumes that the large increase of current is caused by the radiation emitted from the cylinder, it is difficult to understand how the light can act so differently on different parts of the wire surface, especially in view of the fact that even when the wire is freed of impurities by intense heating, the wire still emits

---

1. S. Ratner, Phil. Mag. Vol. 40, p. 785, Dec. 1920

electrons from only a few spots. It seems proper, therefore, to conclude that the electric force itself pulls the electrons out of the surface of the metal.

If one assumes that at ordinary temperatures free electrons move about in a conductor in every direction, then one of the reasons why an electron does not escape from the metal is that as soon as it leaves the metal surface there is an electrostatic attraction between the electron and the metal equal to $e^2/4r^2$, where e is the charge on the electron and r is the distance of the electron from the surface of the metal. One assumes that at ordinary temperatures the kinetic energy of the electrons is not sufficient to allow them to move against this force, but that with increasing temperature the kinetic energy may become such that some of the fast-moving electrons can escape. An application of a strong outside field would tend to either annul or augment the action of the metal on the electron, depending upon the polarity of the applied potential. Hence by the proper application of a very strong field one might expect to free electrons from a metal.

W. Schottky[1], using much this method of attack, divides the distance from an ideally smooth surface into two parts; first, the "Bildkraftsphäre" (2 --4x10^{-7} cm from the surface to the distance of 10^{-4} cm from the surface) in

---

[1] W. Schottky, ZS f. Phys. Vol. 14, p. 63, March 1923.

which region he assumes that the method of images may be used to calculate the force on the electron. The other region, the "Nahewirkungssphäre", takes in the distances from the surface of from 2--4x10^{-7} cm to 0 cm. He postulates that within a critical distance X_0 the electric force on an electron may be considered constant and of a value equal to $e^2/4x_0^2$; and outside this distance he assumes the force as calculated by the method of images to hold, viz., $a^2/4x^2$. Thus the work necessary to carry the electron from the surface to the distance x_0 is $e^2/4x_0$, and the work necessary to carry the electron from x_0 to infinity is $-\int_{x_0}^{\infty} e^2/4x^2\, dx = e^2/4x_0$. Hence the total work becomes, $e^2/2x_0$. Expressed in equivalent volts this is

$$W = 300e / 2\, x_0.$$

Taking the electron affinity of tungsten as 4.5 volts, x_0 can be calculated and is found to be 1.6×10^{-8} cm.

According to these assumptions, the maximum force which the electron experiences in leaving the metal is,

$$E = 300e/4e^2 = 1.4 \times 10^8 \text{ Volt/cm}.$$

As the next step in the argument, Schottky considers the effect of an outside field on this "inside" field and suggests that the former, if properly directed, will cause a decrease of the work necessary to free an electron from the metal. He calculates that an outside field of one million volts per centimeter will penetrate into the inner part of the

"Bildkraftsphäre", a distance of 2.1 $x10^{-7}$ cm from the surface, and will decrease the electron affinity approximately 1/3 of a volt.

Considering ultra-microscopic irregularities on the metal surface, he finds that the electric force may be ten times greater at one of these "molecular" projections than at the ideal surface. Hence the formulas used to calculate the electric force from the geometrical shape and dimensions of the electrodes will give values only 1/10 as great as actually exist at certain small regions on the surface. Taking this into account he finds that the maximum external force, as calculated by geometrical methods, needed to overcome the maximum force which an electron experiences as it moves from tungsten is 10^7 volt/cm.

If this gradient is reached, then the electron current should be independent of temperature. Since the gradients used by Lilienfeld were of the order of 10^7 volt/cm, and the currents found to be independent of temperature, Schottky interprets these results as being in agreement with his theory. The reason for Hoffman getting currents from Platinum at 7.6×10^6 V/cm he explains as being due to the smallness of the currents used; that is, only the electrons with the very highest speeds produced the current, they being able to get out with only a partial penetration of the external field. The almost instantaneous rise of current observed by Lilienfeld when the critical voltage was reached, which, of course, is not in agreement with the theory given above, is interpreted by Schottky as being due to the presence of positive ions which neutralize space charges. He also interprets the X-rays at the cathode observed by Lilienfeld as being due to the striking of electrons into a bank of positive ions which surrounds the active cathode surface.

If we interpret the "field-currents" observed in this investigation as being due to the free electrons which, because of the decrease of the electron affinity caused by the penetration of the field, are able to escape from the metal surface, then it is difficult to understand why the "field-currents" show no change with temperatures as high as 900° K, but begin to show these effects at 1100°K. Had the temperature effect at the higher temperatures not appeared, one might have concluded offhand that the maximum gradient E_m had been reached, making it possible for the conduction electrons to come out of the metal independent of temperature; yet since according to Schottky E_m has a value of ten million volts per centimeter this conclusion would have been incorrect because all the gradients used were of the order of one million volts per centimeter and less. One is not justified, therefore, in the conclusion that the "field-current" electrons are the conduction electrons which because of their kinetic energy and because of the penetration of the field are able to escape from the surface of the metal. Hence a mechanism of electron extraction different from that set up by Schottky must be built.

The most plausible interpretation of the results is to postulate that the electrons which are pulled out of the metal surface are not the free electrons--conduction electrons--but are the loosely-bound electrons of the outermost atoms. It is supposed that when the field in the neighborhood of a surface atom becomes strong enough to pull out an electron, a new electron comes from the inner part of the metal, presumably a conduction electron, and takes its place. Thus so long as the field remains sufficiently great, a continuous stream of electrons from the interior of the metal will pass out by way of this propitious exit. This type of "field-current" would be independent of temperature for temperatures up to the point where thermions begin to appear. Thus one of the most important facts of this investigation is satisfied by this explanation, (Table XVIII).

Now according to this postulate, the increase of the "field-current" at a temperature of 1100° K (Table XIX) is due to a few conduction electrons which, because of the added kinetic energy associated with this temperature, are now able to come into the region where the strong electric field exists, and then be pulled out of the influence of the metal by it. At this temperature, then, the major portion of the "field-current" comes out of the metal through the agency of the loosely-bound atom electrons, the remaining small portion, that part which is added because of the increased temperature, comes directly from the body of conduction electrons. Presumably the reason that the small portion of the current--that due to the temperature effect--does not remain constant at this temperature and become negligible as the larger portion increases to currents of the order of milli-amperes, (Table XX), is that the increasing magnitude of the field enables it to penetrate farther and farther into the molecular and crystalline interstices of the surface and thus to get hold of more and more of the conduction electrons which, because of the kinetic energy associated with the particular temperature, are now able to come into the interstices of the surface. The small portion mentioned above, may become the greater portion of the "field-current" at sufficiently high temperatures.

By applying the method of images Debye[1] has shown that it is easier for an electron to escape from a sharp point than from a flat surface. He shows that if the radius of curvature r of the surface is so large that X_o , a distance from the surface, is small compared with it, then the work necessary to move an electron from x_o to infinity is given by the relation,

$$w = e^2/4x_o - e^2/8r \ .$$

This shows that the work of escape of an electron from a curved surface of radius r is less than that from a plane surface by an amount $e^2/8r$. Hence it follows that if a surface is irregular there will be contact differences of potential between the protrusions and the interstices. If we consider a protrusion and an interstice as being adjacent and each having a radius of curvature of 10^{-6} cm, then the electrostatic force tending to drive an electron from the hill to the hollow will be of the order of several thousand volts per centimeter[2].

A similar effect can be expected when an impurity of different electron affinity is on the surface of the metal. If the impurity has a lower electron affinity than the surface itself, then the impurity will act like a protrusion on the surface. From this it follows that under

---

[1] P. Debye, Ann. d. Phys., Vol. 33, p. 441, 1910.
[2] Van DerBijl, Thermoionic Vacuum Tube, p. 37.

the influence of a strong external field a proper type of impurity located on a surface, and especially that located on a protrusion of the surface, may become a veritable electronic "volcano", hurling forth electrons which were beneath the surface.

Since protrusions of different shapes and sizes will act differently, and since an impurity on a surface may not cover all the protrusions, it is clear that on a wire of the length used in these experiments, only a very few regions will be in a condition to respond to the lower gradients. With increase in voltage will come an increase in the current from these same regions, and new regions will begin to respond because the increased gradient is now able to pull electrons from more difficult spots. This picture accounts for the large increase in "field-current" with potential gradient.

The "field-current-conditioning" process may be interpreted in terms of this picture as being due to the forcing of a few molecules of impurity from the tips of certain protrusions by the outrush of the great electron streams through these portions of the surface. This surface condition remains constant so long as the conditioning current density is not exceeded. The data of Tables X and XI furnish a further justification for the idea that a few molecules of impurity are forced away from the tips of certain protrusions for these data show that heating the wire below 1200° K gives the current-conditioned surface a lower "critical" gradient; and this may be interpreted as meaning that at these temperatures the impurity does not evaporate, but does change about on the surface, covering over that part of the protrusion which was conditioned.

The fatiguing effect shown by the wire which had been conditioned by extreme heat treatment may be interpreted as meaning that a very few tungsten molecules on the outermost part of the protrusions (for now presumably all the impurity has been evaporated off) are removed when the current is large and the gradient is very high. Thus the fatiguing effect shows up for the smaller gradients when the very end parts of the protrusions are needed. Since the fatiguing effect recovers with time, the rearrangement or loss of the molecules of the protrusion tip is not permanent, and presumably the protrusion is built up again by one or two new molecules.

Two types of impurity seem to be on the wire. First, an impurity which moves about on the surface at 1100° K (Table XI) and which evaporates from the surface at a temperature near 1500°K (Tables XIII, XIV). Second, an impurity which appears on the surface at about 2000° and disappears at a temperature of about 2500° K, (Tables XII, XIII, XIV).

This second impurity is no doubt thorium for according to Langmuir[1] if a thoriated filament is heated for a short time at 1900° K, thorium diffuses from the inside of the filament to the surface and gradually completely covers it with a layer of thorium. On the other hand, if the filament is heated for a few minutes at 2800 or 2900°K, all the thorium distills off the filament leaving a surface of pure tungsten. If, however, the thorium is distilled from the filaments at a lower temperature or for a shorter time it is possible to leave the surface so it is partly covered with thorium and partly covered with tungsten. Insufficient investigation makes it impossible at this time to identify the first impurity, but, if the theory here given be correct, it must be an impurity with low electron affinity.

It seems easy to explain the reason for the differences in the values of the "critical" gradient for intense-heat-treated tungsten wires and points. Under the heat treatment the tungsten crystallizes into crystals having an average diameter of about .0003 cm. As viewed through the high-powered microscope interstices between the crystals are seen; in fact the heat-treated wire seems to be more uneven than the untreated. To get two wires with just the same number of high spots of the same size, etc., would be a

---

1. Langmuir-Arnold Interference, p. 57; Langmuir, Physical Review, Vol. 22, p. 357, October, 1923.

difficult task. This no doubt explains why with the same heat treatment the "critical" gradients for the wires differ as much as from 10 to 15 per cent. Also, in view of the fact that, because of a much larger surface, the chances for getting an "easy" spot on a wire is greater than that for the end of a point, it seems reasonable that the maximum "critical" gradients found for the wires were never quite as large as those found using points and plane. Even though different potential gradients were found for the three metals studied in the point and plane experiment, we are not justified in saying that these gradients are characteristic of the metals, because even for the same metal--sharp and dull tungsten points--the gradients were different. How much the differences found for the metals are due to the metals themselves and how much due to the nature of the surfaces is unknown.

It becomes very difficult to say what is the standard experimental condition to use in determining the characteristic gradient of a metal, if perchance such exist. Even if a surface be free from impurity, it contains irregularities which never can be duplicated exactly, and these irregularities determine the numerical value of the gradient.

All experimenters have obtained "critical" gradients of the same order of magnitude, but none have agreed on the numerical values of these gradients. In view of what has been said this is not surprising. If a correct technique of surface conditioning can be found and then agreed upon there will be some hope of finding whether the metals have characteristic "critical" gradients. It is hoped that this investigation has done its bit in establishing such a technique.

SUMMARY

The results of this investigation may be summarized as follows:

1. Electrons may be pulled out of cold metals by intense electrical fields.

2. It appears (p. 29) that positively charged metal atoms may be pulled from a metal surface by a properly directed electric field of intensity somewhat greater than that required for pulling out electrons.

3. The gradient needed to pull electrons out of a metal is controlled by the surface irregularities and especially by the surface impurities.

4. The metal surface may be conditioned by heat treatment and by drawing large currents from the surface. The "critical" potential gradient may be increased fourfold by heat treatment, and twofold by the "field-current" conditioning process.

5. The "field-current" for an unconditioned tungsten surface begins to set in at about 200,000 volts per centimeter and rises over ten millionfold as the potential gradient is increased to one million volts per centimeter. The surface is

conditioned by this run and thereafter, if the maximum current does not exceed the maximum conditioning current, the "field-current" will set in at about 400,000 volts per centimeter and rise over ten millionfold, approximately reversibly, as the gradient is increased to one million volts per centimeter (Figure 9).

6. The rate of increase of the "field-current" with the potential gradient is large when the "critical" gradient is small and vice versa.

7. Large currents drawn from surfaces subjected to intense heat treatment show fatiguing effects which recover with time.

8. The "field-current" in general has its origin in a very few minute surface spots which presumably locate surface impurities, or surface protrusions, or both.

9. The "field-current" is completely independent of temperature between 300° K and 1000° K.

10. The "field-current" is slightly greater at 1100° K than at 300° K.

11. The assumption that the "field-current" is made up of conduction electrons, which are able to leave the metal because of their kinetic energy and the decrease by the external field of the work needed to free them from the surface, is not tenable in view of the results of this investigation.

12. Based on the results of this investigation, a new postulate is set up, viz., that the loosely-bound electrons of the outermost atoms--atoms of impurity of lower electron affinity, or atoms on the tips of protrusions--are pulled away from the atoms by the strong external field and are replaced by new electrons, probably conduction electrons from the interior of the metal. This postulate accounts for the temperature effects (9) and (10) because under this assumption all the "field-current" comes from the loosely-bound electrons and is independent of temperature until a sufficiently high temperature is reached when an added current comes directly from the body of the conduction electrons. At this temperature it is supposed that the conduction electrons have sufficient kinetic energy to enable a few of them to come up into the surface interstices where the external field is sufficiently strong to drag them out (see pages 64 and 72). The postulate also explains the large increase of "field-current" with potential gradient, the current conditioning process, the fatiguing effect shown by surfaces which have been subjected to intense heat treatment, the fact that the "field-current" has its origin in a few minute surface spots; it enables one to interpret the effects of heat treatment as being due to the movement over and the evaporation from the surface of

impurities of low electron affinity; and it explains clearly why the "critical" gradients found for intense heat-treated tungsten surfaces (presumably clean surfaces) can be different.

13. Because of the control which surface conditions have upon "critical" gradients, it seems unlikely that any of the results so far given by investigators can be taken as the true characteristic "critical" gradients of the metals, if perchance such characteristic gradients exist.

In conclusion the author wishes to thank Dr. Robert A. Millikan for suggesting the problem, for aiding in the interpretation of the results, and for placing at the author's disposal the equipment of the laboratory, the facilities of the shops, and the help of the technical assistants, Mr. Julius Pearson, Head Instrument Maker, and Mr. William Clancy, Glass Blower.

Norman Bridge Laboratory of Physics,
California Institute of Technology,
Pasadena, California,
August 30, 1923.