The Effect of Temperature on the Emission of Electron Field Currents from Tungsten and Molybdenum*

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Electron field currents from the central portion of long molybdenum and tungsten filaments about 2.7×10^{-3} cm in diameter have been studied. The field currents were first made stable to about 5 percent by long-continued conditioning treatments of temperature and high voltage under high vacuum conditions. Thermionic emission measurements gave the values 4.32 and 4.58 volts for the work function of the molybdenum and tungsten, respectively, in good agreement with the accepted values for the clean metals. Emission measurements were then made at fields varying from about 5×10^5 volts/cm to about 1×10^6 volts/cm and at temperatures varying from 300°K to about 2000°K. Down to about 1600°K the thermionic currents completely masked the field currents. Thermionic emission values below 1600°K were obtained by extrapolation. Thus the field currents at the lower temperatures were separated from the thermionic currents. Where necessary, corrections were made for the decrease in the voltage gradient accompanying the thermal expansion of the filament. The field currents were found to be independent of temperature to within 5 percent from 300°K to 1400°K. At temperatures higher than 1400°K the data are consistent with the assumption that the current consists of a thermionic current plus a current which is independent of temperature. However, because of the exponential change of thermionic current with temperature a small effect of temperature on the field current could not be distinguished at temperatures higher than 1400°K. From the theory of Fowler and Nordheim, β, a factor introduced by surface irregularities, is found to be 120 for the tungsten cathode and 47 for the molybdenum one. Thus for tungsten, Houston's theory of the temperature effect is in approximate agreement with the negative results of these experiments.

INTRODUCTION

THE effect of temperature on electron field currents was originally investigated by Millikan and Eyring.[1] With a thoriated tungsten cathode they first observed a decrease of the critical gradient, i.e., the value of the field strength at the surface just sufficient to produce a perceptible outflow of electrons, at about 1100°K. This was interpreted as an effect of temperature on field currents rather than as the onset of a perceptible thermionic current. Since it is not known whether in respect of thermionic properties the metal would behave like a tungsten surface which is clean or one which is contaminated with free thorium, this interpretation is not free from question.

DeBruyne[2] used tungsten in similar studies. On the basis of measurements by Pforte[3] and DeBruyne[4] he calculated the thermionic emission from the Richardson equation and the theory of the Schottky effect.[5] Subtracting this from the measured currents he obtained what he regarded as the field current emission and plotted it as a function of field strength and temperature. He then represented the variation of field currents with field strength at temperatures from 293°K to 1944°K by a single curve about which the points are rather widely scattered. It is concluded that within the experimental error, the field currents are independent of temperature from 293°K to 1944°K.

There are two serious possibilities of error in this proposed way of distinguishing the field current and the thermionic current. In the absence of direct measurements, the correct value for the work function of the cathode to be used in the Richardson equation is uncertain. Then there are the usual difficulties in a determination of the absolute magnitude of the filament temperature which is necessary for estimating the thermionic

* Presented before the American Physical Society in Washington, D. C., April, 1933.

[1] Millikan and Eyring, Phys. Rev. **27**, 51 (1926).

[2] DeBruyne, Proc. Camb. Phil. Soc. **24**, Part 4, 518 (1928).

[3] Pforte, Zeits. f. Physik **49**, 46 (1928).

[4] DeBruyne, Proc. Roy. Soc. **A120**, 423 (1928).

[5] Schottky, Phys. Zeits. **15**, 872 (1914).

emission. These are serious since the absolute magnitude of both the work function and the temperature are involved exponentially.

By drawing separate lines through the data taken at each separate temperature, Millikan and Lauritsen[6] obtain a series of curves from the DeBruyne[2] data which they believe shows an increase of field current with temperature.

In the latest publication on this subject, DeBruyne[7] calculates that the thermionic emission from fully activated thoriated tungsten would explain the current increase which Millikan and Eyring[1] interpreted to be a field current temperature effect. He then automatically obtained a continuous record of the field currents at a given field as a tungsten filament was alternately heated to various temperatures and cooled to room temperature. Below 1600°K his records do not show a consistent temperature variation greater than the spontaneous fluctuations in the current. The increase in current at 1600°K is attributed to thermionic emission. DeBruyne concluded that while there may be a temperature effect on field currents no real variation has yet been observed.

The contradictory deductions from the above experiments occur because it is uncertain whether the cathode surface is clean or contaminated and because the thermionic emission correction is uncertain. I therefore investigated the effect of temperature on field currents from filaments of tungsten and molybdenum of which the surfaces were proved by study of their thermionic emission to be clean. The correction due to the thermionic emission was determined by extrapolation of the measurements. In this way the uncertainty as to the exact value of the work function, the temperature, the applied field and the variation of current with field is minimized.

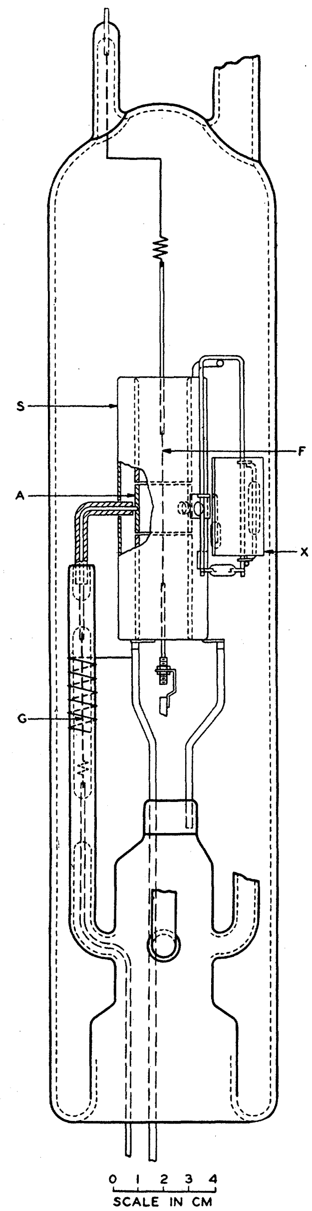

FIG. 1. The experimental tube.

Apparatus

The experimental tube is shown in Fig. 1. The anode A is a nickel cylinder 2 cm long and 2 cm in diameter. The cathode consists of a filament F about 2.7×10^{-3} cm in diameter and 6 cm long, and is mounted on the axis of the cylindrical anode. The average applied field in volts/cm is obtained by multiplying the applied voltage by the factor G, the approximate value of which is 100 cm^{-1}. To prevent a displacement of the filament by the strong electric field, a certain tension is applied to it by means of the calibrated spring and the bolt and nut arrangement shown. In this way the tension is decreased as the temperature is increased and the filament does not pull apart. The anode has cylindrical guard rings 4 cm long

[6] Millikan and Lauritsen, Phys. Rev. **33**, 598 (1929).

[7] DeBruyne, Phys. Rev. **35**, 172 (1930).

and 2 cm in diameter. End effects due to filament leads, end cooling of the filament, and distortion of the electric field at the ends of the anode are in this way eliminated. A cylindrical shield S attached to these guard rings completely surrounds the outside of the anode. The electrical lead from the anode is completely shielded by quartz and glass until it passes through the glass envelope. The guard ring G on the glass tubing encasing this lead prevents any surface leakage of electrons from reaching the anode A. Throughout the experiments, currents to the anode A are the only ones measured. The guard rings and shield S are such that the only currents which can reach the anode come from the central portion of the filament which is uniformly heated and at which the average electrical field is constant and known.

Voltages up to about ten thousand volts were used. Steady d.c. voltages were obtained from a 220-volt a.c. source by means of transformers, rectifiers and filters. The voltage was measured with an ordinary high resistance voltmeter in series with the proper resistors.

Current measurements were made with a d.c. vacuum tube amplifier and a series of grid leaks. These measurements ranged from about 10^{-12} amp. to 10^{-4} amp.

The filament temperature was determined from the temperature heating current data of Worthing[8] for molybdenum and Jones and Langmuir[9] for tungsten. The filament heating current was measured with a standard resistance and a Leeds and Northrup Type K Potentiometer. The filament diameter was determined from the mass of a measured length of the wire.

High vacuum technique of the sort already reported[10] was employed in the pumping of the tubes. Before the tubes were removed from the pumps some field currents were drawn from the cathodes. After the tubes were removed from the pumps, the filaments were heated at high temperatures for many hours, sufficient to age them according to the procedure of Worthing[8] and Jones and Langmuir.[9]

The filaments were also conditioned by applying voltages at least as high as were used in any of the subsequent measurements. These first applications of the high voltage produced extensive fluorescence on the glass walls of the tube, the shield S and the inside surface of the anode A and its guard ring cylinders. The fluorescence on the glass was blue, that on the metal (nickel) red. In both cases, the patches of light were quite intense and fluctuated much both in position and intensity. Some patches were quite diffuse and some quite sharply defined. Usually the fluorescence which appeared at any given voltage would soon vanish if the voltage continued unchanged, although this was not always so. These fluorescence effects emphasize the importance of the shield S of the experimental tube.

Eventually, the high temperature and high voltage treatment established conditions such that at a given voltage the field current was constant to within about 5 percent over periods of hours and was not affected by temperature treatments at 2000°K. Throughout the temperature studies recorded here the pressure was about 1 or 2×10^{-8} mm Hg.

Method

When this stability of the field currents was established the effect of temperature on field currents was investigated as follows. The thermionic characteristics of the cathodes were first measured to insure that they agreed with those for clean surfaces. With the field kept at some constant value, current measurements were then made by varying the temperature from about 300°K to about 2000°K. After each temperature setting above 300°K the filament would be reduced to 300°K (room temperature) for a current measurement. In this way any small trend in the room temperature value of the field current, due to whatever cause, was recorded. Current and voltage were always measured together. Measurements of this sort were made on molybdenum from 8×10^5 volts/cm to 1×10^6 volts/cm and on tungsten from 5×10^5 volts/cm to 1×10^6 volts/cm.

Results for Tungsten

Fig. 2 gives the thermionic characteristics of the tungsten filament. The average value for the

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[8] Worthing, Phys. Rev. **28**, 190 (1926).

[9] Jones and Langmuir, G. E. Review **30**, No. 6, June, 1927.

[10] Ahearn, Phys. Rev. **38**, 1858 (1931).

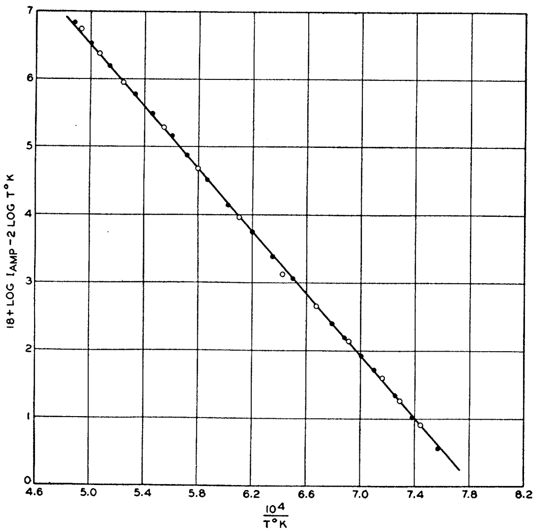

FIG. 2. Richardson plot of thermionic emission from tungsten. $F=1.2\times 10^4$ volts/cm. Dotted circles for decreasing temperatures; open circles for increasing temperatures.

work function Φ is 4.58 volts and for the constant A of the Richardson equation 73 amp./cm² deg². This value of Φ agrees well with 4.52 volts, the average of the most satisfactory data on tungsten.[11] The field current measurements are therefore characteristic of a clean tungsten surface.

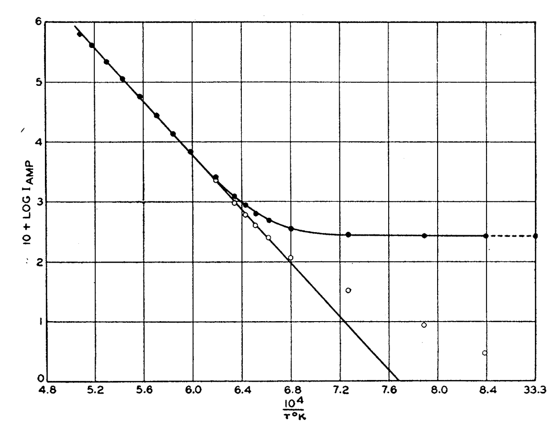

FIG. 3. Electron emission from tungsten at $F=9.47\times 10^5$ volts/cm. Dotted circles are experimental points; open circles show the difference between measured currents and current at 300°K.

Figs. 3 and 4 give emission-current *vs.* temperature data at two values of the applied field,

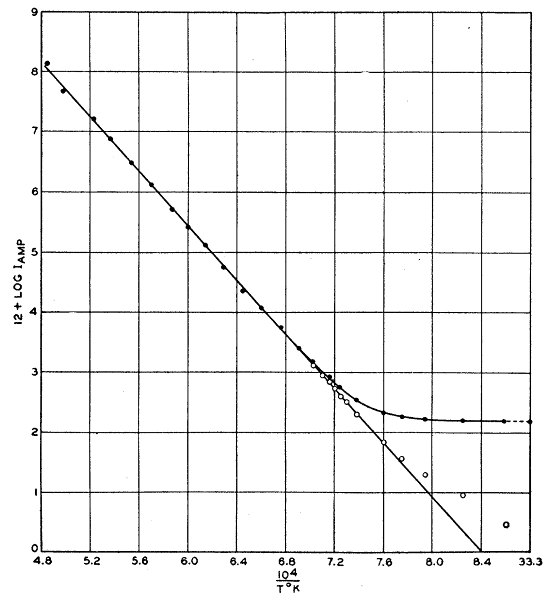

FIG. 4. Electron emission from tungsten at $F=5.42\times 10^5$ volts/cm. Dotted circles are experimental points; open circles show the difference between measured currents and current at 300°K.

the coordinate system being that familiar in thermionics in which points lie along a straight line if they conform to the Richardson equation. One infers that down to about 1600°K for one field strength and down to 1400°K for the other, the thermionic current completely submerges the field current, for the data lie along a straight line when plotted according to the Richardson equation. This linear portion of the experimental curve is extrapolated to lower temperatures and assumed to give the values of the thermionic emission there. The difference between the experimental curve and this extrapolated curve is interpreted as the field current. Corrections to the field required by voltage variations or thermal expansion[12] of the filament are negligible for the tungsten data. In Table I these field current values are expressed as percentages of the field current at room temperature. At the lower temperatures, these percentages have an approximately constant value near 100 percent. However, at the higher temperatures they depart from this constant value. This is easily understood from Figs. 3 and 4. As the experimental and extrapolated curves approach each other, the error involved in a determination of the difference in their ordinates increases.

[11] Dushman, Rev. Mod. Phys. 2, 394 (1930).
[12] Bridgman, Phys. Rev. 34, 1411 (1929).

The points marked with open circles on Fig. 3 are obtained by subtracting the room temperature value of the field current from the observed currents at the various temperatures. If the field current is independent of temperature, these differences should be values of the thermionic current and accordingly the points should be on the extrapolated straight line. As a matter of fact they fall nicely on the extrapolated straight line down to 1450°K. At lower temperatures the amounts by which these points are displaced from the straight line are well within the experimental error in their determination. For example consider the point at $10^4/T=7.3$. This calculated thermionic emission is 8 percent of the total current measured while the straight line predicts that the thermionic emission would be 3 percent of this total current. Since the experimental error in the current measurements is about 5 percent this seemingly large discrepancy between the two values of the thermionic emission is not significant. Thus in Figs. 3 and 4 there is determined a temperature T_L above which the calculated thermionic emission agrees as well with the Richardson equation as do the direct measurements of the thermionic emission as shown in Fig. 2. Therefore it follows that above T_L the data are consistent with the assumption that the measured current consists of a thermionic current plus a field current which is independent of temperature. However, because of the exponential change of thermionic current with temperature a small effect of temperature on the field currents could not be distinguished. This analysis was made on all of the data given in Table I where T_L is located by the horizontal lines.

TABLE I. *Tungsten cathode. Ratio of field current at temperature T to that at 300°K.* T_L (indicated by the horizontal lines) is the temperature above which the measured emission minus the emission at 300°K is described by the Richardson thermionic emission formula.

$10^4/T$ (°K)	T (°K)	Field, (v/cm) $\times 10^{-5}\rightarrow$ 5.31	5.36	5.42	6.25	6.25	7.00	7.00	7.10	7.10	7.63	7.95	7.95	8.65	8.65	9.47	9.47	9.64	10.56
33.3	300	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
9.5	1050																	96	
9.4	1065																		
9.3	1075																		
9.2	1085																		
9.1	1100																	99	
9.0	1110																		
8.9	1125																		
8.8	1135			101	97	99	101					103						102	
8.7	1150			100	98	98		101											
8.6	1165		107	100	99	98													
8.5	1175		107	103	100	98				106	107		106		101				
8.4	1190		107	103	100	98	100	102		106	107		106			101	104		105
8.3	1205	106	107	103	101	98				106	107		104					106	
8.2	1220	104	107	104	102	97				106	107		107		103				
8.1	1235	106	107	102	102	97				106	103		107						
8.0	1250	109	107	99	103	97	100	106	104	106	103	103	107	111	106		100	105	
7.9	1265	111	107	100	103	96	100		104	108	110		107	111	107	100	102	105	
7.8	1280	111	107	101	103	97	100		108	106	110		104	110	107	104	104	105	
7.7	1300	112	107	107	103	96	100		108	108	110		104	109	105	104	106	105	
7.6	1315	112	107	111	104	96	101	106	108	108	112	102	109	108	103	104	107	105	
7.5	1335	114	107	114	105	97	103	106	108	111	112	102	109	109	105	102	105	105	
7.4	1350	124	107	124	105	97	105	108	108	114	112	102	111	109	107	106	105	105	
7.3	1370	143	107	137	105	99	108	109	112	118	112	103	114	112	110	108	108	105	96
7.2	1390	162	107	170	103	101	113	111	125	123	107	103	121	112	110	108	108	110	100
7.1	1410	190	111	209	109	101	117	116	117	133	118	103	121	110	111	108	108	110	100
7.0	1430	267	111	235	112	95	120	122	129	141	121	102	123	108	111	104	108	110	95
6.9	1450					85	120	128	142	157	129	102	128	106	107	104	106	110	93
6.8	1470					60	114	125	154	168	146	98	137	101	101	98	103	114	93
6.7	1490						114	125	158		148	87	156	95	91	96	101	110	95
6.6	1515										143		191	82		87	91	109	101
6.5	1540										143					70	77	113	103
6.4	1560																	109	94
6.3	1590																	95	
6.2	1610																		
Average below T_L		106	105	103	100	98	101	103	104	106	105	102	109	107	105	101	103	103	99
Average ratio 103%																			

Below T_L the effect of temperature on field currents can be determined from Table I. When these data are averaged, equally weighing all parts of the temperature range below T_L, a value of 103 percent is obtained. If this value were 100 percent it would mean, of course, that the field currents were completely independent of temperature.

Results for Molybdenum

Fig. 5 shows the early history of one particular molybdenum cathode. On the ordinate the logarithm of field current is plotted. The applied field had the constant value 8.05×10^5 volts/cm. One sees that, during the portion of the filament history given here, the "field current activity" decreased by a factor of about 35,000. A large decrease in activity of this sort is always observed during the early stages of treatment of a filament. However, just as shown in Fig. 2, one type of treatment sometimes increases the activity while again it may produce a decrease. This applies quite generally to all the types of treatments shown in Fig. 2. At times in the early history of a filament with a constant applied voltage, spontaneous increases of as much as 30,000 would occur. In some of these cases the current would be reduced to its former value by heating the filament to only 1000°K for a few minutes.

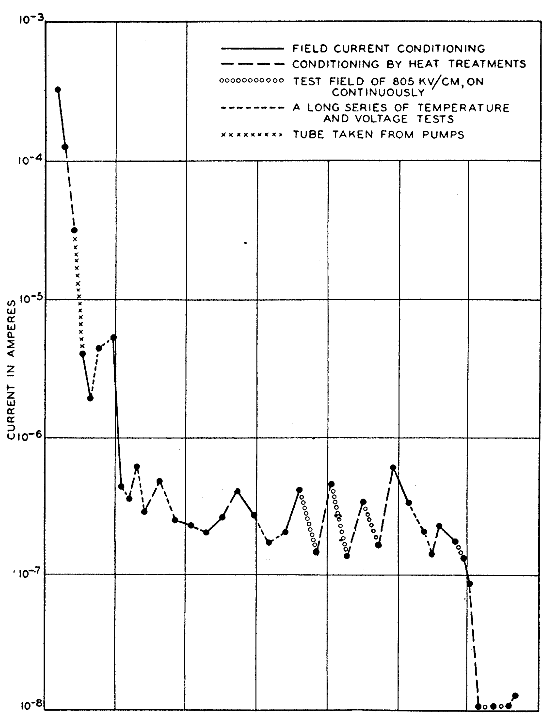

Fig. 5. Early life history of a molybdenum filament. A test field of 805 kilovolts/cm was used. The time extended over about 20 days.

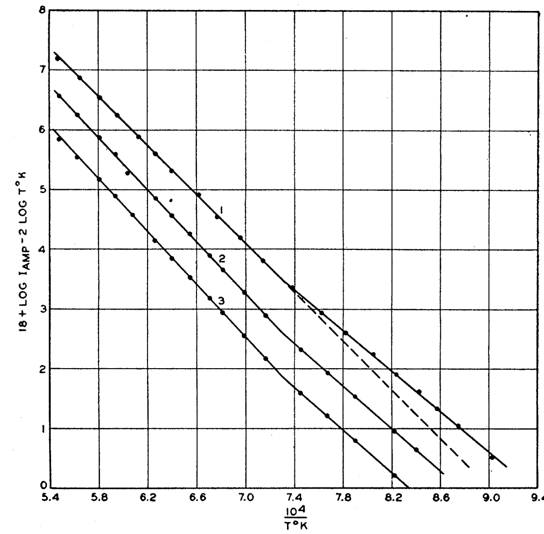

Fig. 6. Richardson plot of thermionic emission from molybdenum. Curve 1, $F=4.4\times10^5$ volts/cm; curve 2, $F=1.0\times10^4$ volts/cm; curve 3, $F=1.0\times10^3$ volts/cm. Add 0.6 to ordinate.

Fig. 6 shows the thermionic characteristics of the molybdenum filament, where the data are plotted according to the Richardson thermionic emission equation. The electric fields were 10^3, 10^4, and 4.4×10^5 volts/cm, values much too small to give field currents measurable in this experiment. The data are not fitted by a single straight line but require two straight lines which intersect at about 1400°K. The slope of the low temperature line in all three cases is 20 percent lower than that of the high temperature one. The explanation of this nonlinearity is not yet known and will be further investigated.* It cannot be attributed to end cooling of the filament because such an effect would produce an increase in slope.

A contamination of the filament by gases at the lower temperatures might produce such an

* This same nonlinearity has again appeared in similar measurements which have just been made on another molybdenum filament.

effect. There is, however, no definite evidence in favor of this idea. A thermionic emission measurement at one of these low temperatures immediately after hours of heating at the highest temperature gave a point on the curve of Fig. 6. Furthermore a measurement made at a low temperature after the filament had been at room temperature many hours gave a point on the curve also.

Regardless of the explanation of this nonlinearity, it is clear that, given the thermionic data above 1400°K, one does not obtain the correct values below 1400°K by extrapolating the straight line. Instead, one must insert a straight line whose slope is 20 percent less than that for the emission above 1400°K.

The high temperature portions of these curves give for the work function Φ the value 4.32 volts and for the constant A of the Richardson equation 200 amp./cm^2 deg^2. Dushman[11] chose 4.41 electron-volts as the average of the most reliable data for the work function of clean molybdenum. The more recent measurements of DuBridge and Roehr[13] give the value 4.15. My value of 4.32 is in

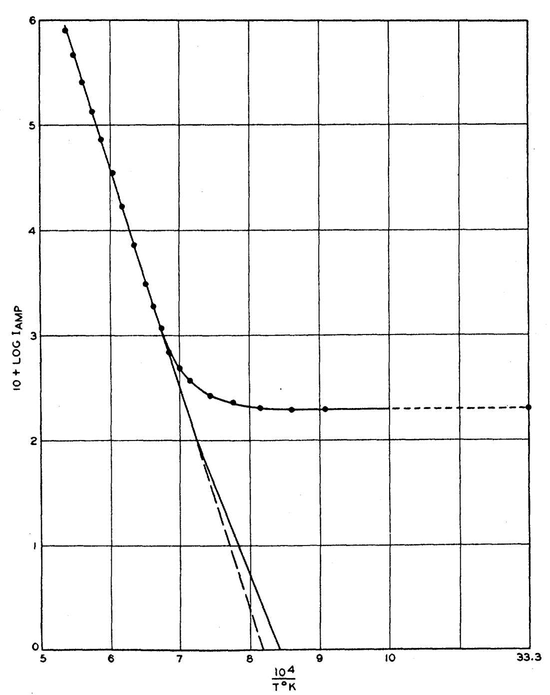

FIG. 7. Electron emission from molybdenum at $F=1.05 \times 10^6$ volts/cm. The intersecting straight lines give the thermionic emission.

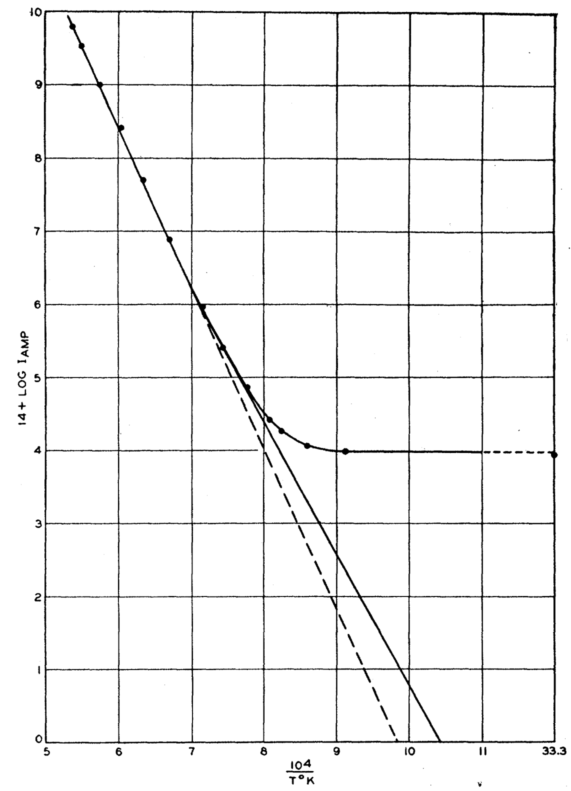

FIG. 8. Electron emission from molybdenum at $F=8.13 \times 10^5$ volts/cm. The intersecting straight lines give the thermionic emission.

good agreement with the average of these measurements. The field current measurements are therefore characteristic of a clean molybdenum surface.

Figs. 7 and 8 give emission current *vs.* temperature data for the highest and lowest fields used. One observes that down to about 1400°K or 1500°K, depending on the applied field, the thermionic current completely submerges the field current since the data lie on a straight line according to the Richardson equation. We draw a line whose slope is 20 percent smaller and which intersects the other line at about 1400°K, extrapolate it, and assume that it gives the values of the thermionic current at these lower temperatures. The current corresponding to the difference between the experimental curve and this extrapolated curve for the thermionic emission is assumed to be the field current. In Table II, its

[13] DuBridge and Roehr, Phys. Rev. **42**, 52 (1932).

TABLE II. *Molybdenum cathode. Ratio of field current at temperature T to that at 300°K.* T_L (indicated by the horizontal lines) is the temperature above which the measured emission minus the emission at 300°K is described by the Richardson thermionic emission formula.

Field, (v/cm) $\times 10^{-5}\rightarrow$ $10^4/T$(°K)	T(°K)	8.05	8.05	8.13	7.97	7.97	8.13	8.75	8.75	8.75	8.75	8.75	9.46	9.46	9.46	9.56	10.4	10.4	10.4
33.3	300	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
9.5	1050	100	97	106	110	106	107	114	100	102	97	100	104	105	100	100	103	106	100
9.4	1065	100	94	107	110	106	108	114	100	102	97	100	104	105	100	103	103	106	105
9.3	1075	101	97	107	110	108	108	114	100	102	97	100	104	105	100	103	103	106	105
9.2	1085	101	94	107	112	108	108	114	100	102	97	102	104	105	100	103	103	106	105
9.1	1100	101	94	107	112	108	108	114	100	102	97	102	104	105	105	103	103	106	105
9.0	1110	100	89	107	110	110	107	118	99	102	95	102	104	105	105	103	103	106	105
8.9	1125	100	84	106	110	106	107	118	99	102	95	102	104	105	105	103	103	106	100
8.8	1135	99	100	106	110	106	106	121	99	102	95	102	104	105	105	105	103	106	100
8.7	1150	97	89	106	112	104	106	121	99	102	95	102	104	105	105	105	103	106	100
8.6	1165	94	51	105	118	100	105	118	99	100	95	102	104	105	110	105	103	106	100
8.5	1175	91	41	105	120	94	102	121	99	98	95	102	109	105	110	103	103	106	100
8.4	1190	86	35	105	128	88	99	118	97	98	97	102	109	105	110	103	103	106	100
8.3	1205	75	27	105	130	81	98	111	96	97	95	103	109	105	110	103	103	106	100
8.2	1220	65		107	125	73	90	100	95	94	95	102	109	105	110	103	103	106	105
8.1	1235	48		103	122	56	79	86	93	92	94	102	109	105	110	103	103	106	105
8.0	1250	29		103	100	38	61	64	90	89	90	98	104	105	110	100	103	106	105
7.9	1265			103	100		37		89	84	86	92	104	100	110	100	100	106	105
7.8	1280			103	75				87	81	81	84	100	95	105	95	100	106	105
7.7	1300			115					85	78	73	75	100	95	105	92	97	112	105
7.6	1315			161					85	72	69	62	104	89	110	92	97	112	105
7.5	1335								87	67	64	55	100	89	110	89	90	112	110
7.4	1350								87	62	48	31	109	84	115	89	87	112	105
7.3	1370								100	94	64	47	114	95	130	92	80	118	105
7.2	1390								163	156		94	155	110	175	100	80	130	105
7.1	1410								125				136	89	175	89	77	124	100
7.0	1430												114		150	70	73	112	84
6.9	1450																60	82	63
6.8	1470																40	30	32
Average below T_L Average ratio 103%		98	94	106	110	105	106	115	99.5	102	96	101	105	103	106	102	102	104	103

values, corrected for changes in the applied field because of voltage variations and expansion of the filament on heating, are expressed as percentages of the field current at room temperature. Several sets of data at each of the applied fields used are given. Just as in the data on tungsten, the temperature T_L is indicated by the horizontal lines. From Table II one can calculate the effect of temperature on the field currents from molybdenum. When these data are averaged equally weighing all parts of the temperature range below T_L a value of 103 percent is obtained.

DISCUSSION

These phenomena then are the field-current *vs.* temperature characteristics of clean surfaces, where the work function of the surface in comparison with that known to be characteristic of a clean surface is taken as the criterion of cleanliness. The measurements presented here extend over a considerable range of field and temperature thus giving a wide assortment of relative magnitudes of field current and thermionic current as well as a wide range of field currents. Tables I and II show that the results are quite independent of the value of the applied field.

One sees as in Figs. 3 and 4 and in Tables I and II that the temperature T_L above which the measured current minus the room temperature field current falls on the thermionic line decreases with decreasing field. No doubt if one made measurements at a sufficiently low field this linearity could be extended down to a much lower temperature.

The data for tungsten and molybdenum in Tables I and II below T_L give an average value of about 103 percent for the ratio of the high temperature field currents to the field currents at room temperature. This cannot necessarily be interpreted as a 3 percent temperature effect because the experimental errors amount to 5 percent. It is true that the percentages given in Tables I and II are largely above 100 percent. It is possible that when the filament temperature is raised the filament bows enough to give a small increase in the average applied field. However, there is no evidence that the filament bows on being heated.

THEORY *vs.* EXPERIMENT

Houston[14] developed a formula for field currents as a function of field strength and temperature, which in working form is as follows.

$$I = Ge^{-B/F}(HF^2 + D\Phi T^2), \tag{1}$$

where F is the field in volts/cm, T is the temperature in degrees (absolute), $H = 2.52\times10^{-24}$, $D = 6.67\times10^{-16}$, Φ is the work function in electron-volts. The ratio $R = D\Phi T^2/HF^2$ determines the effect of temperature on field currents. At a field of 10^6 volts/cm, where most of the experiments on the temperature effect have been performed, Eq. (1) predicts an increase in field current of about one thousand percent from 300°K to 1000°K. The order of magnitude of the effects observed experimentally, is predicted by the theory at a field of about 10^8 volts/cm.

This discrepancy may be explained by assuming that because of surface irregularities, over the effective areas of emission the field is greater than the average field by a factor of about 100.

Fowler and Nordheim[15] obtain the following formula for field currents.

$$I = 6.2\times10^{-6}\frac{\mu^{\frac{1}{2}}}{(\Phi+\mu)}\Phi^{\frac{1}{2}}F^2e^{-6.8\times10^7\Phi^{3/2}/F}. \tag{2}$$

Stern, Gossling and Fowler[16] set $F = \beta F_m$, where F_m is the average field calculated from the average dimensions of the filament and β is a factor introduced by the surface irregularities. Thus from Eq. (2) they get the following relations.

$$(d\log_{10} C/F_m^2)/dF_m^{-1} = (-2.94\times10^7\Phi^{3/2})/\beta \tag{3}$$

$$\log A = \log C - \log 6.2\times10^{-6} - \log\frac{\mu^{\frac{1}{2}}}{(\Phi+\mu)}\Phi^{\frac{1}{2}} - 2\log\beta F_m + \frac{2.94\times10^7\Phi^{3/2}}{\beta F_m}, \tag{4}$$

where C is the total current in amperes, A is the emitting area in square centimeters, μ is the usual parameter of the electron distribution in the Fermi-Dirac statistics, Φ is the work function of the metal in electron-volts, F_m is the applied field in volts/cm.

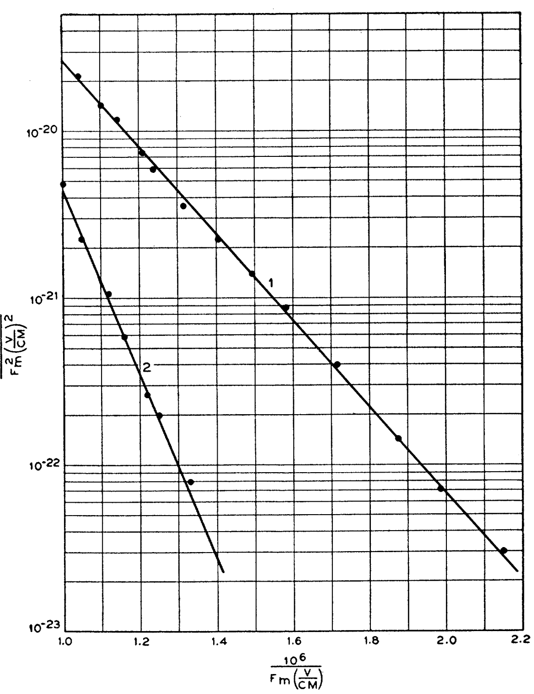

FIG. 9. Electron field currents from pure tungsten and molybdenum. Curve 1, tungsten; curve 2, molybdenum.

The 300°K data embodied in Tables I and II are shown in Fig. 9. From it the values of β and A given in Table III are obtained by using Eqs. (3) and (4). Published data of others[2,17,18] yield for tungsten,* values of β ranging from 24

TABLE III.

	β	A
Tungsten	120	1×10^{-15} cm²
Molybdenum	47	1×10^{-12} cm²

[14] Houston, Phys. Rev. **33**, 361 (1929).

[15] Fowler and Nordheim, Proc. Roy. Soc. **A119**, 172 (1928).

[16] Stern, Gossling and Fowler, Proc. Roy. Soc. **A124**, 699 (1929).

[17] Millikan and Lauritsen, Proc. Nat. Acad. Sci. **14**, 45 (1928), Fig. 2.

[18] Piersol, Phys. Rev. **31**, 441 (1928), Fig. 3.

* Φ was assumed to be 4.6 electron-volts in these calculations.

to 210. Values of β as high as 200 were obtained early in the life of some of my molybdenum* filaments. Eq. (1), with $\beta=120$, predicts a temperature effect of from 10 to 30 percent at 1000°K for the range of fields used with tungsten. Experiment shows this effect to be less than 5 percent. For molybdenum the theory predicts a temperature effect of 50 percent or more contrasted with the negative results of the experiment.

If one could make field-current temperature measurements at a value of βF_m as low as 10^6 volts/cm, the large effect predicted could be definitely verified or disproved. Measurements of this sort are being attempted.

* Φ was assumed to be 4.3 electron-volts in these calculations.

Conclusion

These measurements therefore clearly demonstrate that electron field currents from clean tungsten and molybdenum are independent of temperature to within 5 percent from 300°K to about 1400°K. Furthermore above 1400°K the data are consistent with the assumption that the measured current consists of a thermionic current plus a field current which is independent of temperature. However, the rapid rise of thermionic current with temperature would make it impossible to discern a small effect of temperature on field currents at temperatures higher than 1400°K.

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