ELECTRON EMISSION FROM TUNGSTEN, MOLYBDENUM AND TANTALUM

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Abstract

Thremionic emission from tungsten, tantalum and molybdenum as a function of temperature.—The tubes used in these series of careful measurements, each contained a long V-shaped filament and an anode consisting of a calcium surface deposited on the wall, and were thoroughly heat treated so as to get rid of adsorbed gases. The data obtained were corrected for lead losses and for the Schottky effect. *In the case of tungsten,* specially prepared pure metal was used and the temperature scale of Worthing and Forsythe was adopted. The results for a number of filaments agree well with each other and with the equation $I=AT^2e^{-b_0/T}$ where if I is in amp./cm^2, A has the value 60.2 ($\log_{10}A = 1.779$), the value derived by Dushman[1] from the "chemical" constant, assuming the Sackur-Tetrode theory, and $b_0 = 52{,}600 \pm 250$, which is in good agreement with previous results. *With tantalum,* the accuracy of the results is not as great because of uncertainty as to the temperature scale, but the indication is that the value of A is the same as for tungsten (the most probable value of $\log_{10}A = 1.7 \pm .1$). Assuming the theoretical value, b_0 comes out $47{,}800 \pm 500$. *With molybdenum,* the variation in the results for different runs indicates that the surfaces were not sufficiently cleaned and were contaminated with oxide which would tend to raise the value of A. (The mean value of $\log_{10}A$ obtained is about 2.2.) However assuming $\log_{10}A = 1.779$, b_0 comes out $50{,}000 \pm 500$. *Theoretical constancy of A.* It is pointed out that theoretically A can be expected to be a universal constant only for surfaces for which the surface heat due to positive charge is zero. Experiments with coated filaments show that electronegative atoms like oxygen increase A and electropositive elements like Th and Cs decrease A.

Introduction

As SHOWN by O. W. Richardson and subsequent investigators, thermodynamical considerations lead to an equation of the form

$$I = AT^2\epsilon^{-b_0/T} \tag{1}$$

where I = electron emission per unit area, and b_0 = work function for the emitting surface.

In a previous paper by S. Dushman,[1] it was shown that if the evaporation of electrons is regarded as analogous to that of a monatomic vapor, the value of the constant A in the above equation may be derived from that of the "chemical" constant. If we adopt the Sackur-Tetrode theory,

$$A = 2\pi k^2 me/h^3\ . \tag{2}$$

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[1] S. Dushman, Phys. Rev. **21**, 623 (1923)

On the other hand, Lewis, Gibson and Latimer[2] have suggested another derivation for the chemical constant which leads to the relation

$$A=\left(\frac{2^{5/2}\pi^{9/2}\epsilon^{-5/2}}{15}\right)k^2me/h^3. \tag{3}$$

In these equations,

k = Boltzmann constant $=1.372\times10^{-16}$ erg/degree;

m = mass of electron $=8.995\times10^{-28}$ gm;

e = charge on electron $=4.774\times10^{-10}$ e.s.u.;

h = Planck's constant $=6.55\times10^{-27}$ erg. sec.

Substituting these values in the above equations and expressing I in amperes per square centimeter

$A=60.2$ according to (2);

$A=51.2$ according to (3).

As was furthermore shown in the paper mentioned previously,[1] it is impossible at present to decide on the basis of experimental data definitely in favor of either theory. However, if we adhere to the standard temperature scale for tungsten as established by the work of Worthing and Forsythe,[3] the electron emission data for tungsten are in better agreement with the value $A=60.2$ amps/(cm^2 deg.^{2}).

For the purpose of calculation by ordinary logarithms, Eq. (1) can be written in the form

$$\log_{10}(I/T^2)=1.779-(b_0/2.303T). \tag{4}$$

If a series of emission data is taken at different temperatures for the same metal, it is possible to calculate a value of b_0 from each determination by means of Eq. (4), assuming that $\log A=1.779$. The value of b_0 can also be obtained by plotting $\log(I/T^2)$ against $1/T$. If the equation is valid, the points thus obtained should all lie on a straight line and the value of b_0 from the slope of this line should agree with the average of the values obtained by applying Eq. (4).

The purpose of the following experiments was to determine whether this equation holds for tungsten, molybdenum and tantalum.

DESCRIPTION OF TUBES USED FOR EMISSION DATA

The tubes used for measuring electron emission were constructed as shown in Fig. 1. These were made of lime-glass and were approximately 3 cm in diameter and 20 cm in over-all length. The filament F whose

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[2] Lewis, Gibson and Latimer, J. Amer. Chem. Soc. **44**, 1008 (1922)

[3] A. G. Worthing and W. E. Forsythe, Phys. Rev. **18**, 144 (1921). This scale is based on the following values: melting point of Au = 1336°K (m.p. of Pd = 1828°K) and C_2 (in Wien-Planck equation) = 14350 microns × deg. K.

emission was to be determined, was usually V-shaped and had a total length of 10 or 15 cm. The leads through the glass were of fairly heavy "dumet" wire (such as used in lamp practice), and a short length of molybdenum wire was inserted between the dumet and the filament itself. The anode was prepared in each tube by evaporating calcium from the tungsten wire spiral *S*. In order to obtain electrical connection with the calcium volatilized on the walls, two platinum wires *P* were sealed so that the wire inside the wall was just flush with the surface. The resistance of the deposit as measured between these two seals was always below 1 ohm.

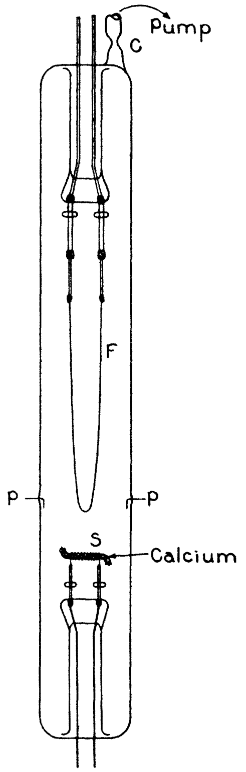

Fig. 1. Design of tube used for determining emission data.

The procedure in preparing such a tube for a series of measurements was as follows. The tube was exhausted by means of a condensation pump with simultaneous bake-out of the glass walls at 360°C for 1 hour. After allowing the tube to cool down, the filament *F* was flashed for a few minutes at a high temperature (2700° to 2800°K in case of tungsten) and then run at a somewhat lower temperature for an hour until all gas evolution had practically ceased. The spiral *S* was then raised gradually to a red heat and the calcium volatilized on the walls. The exhaust was then continued for a few minutes longer and the tube finally sealed off at *c*.

Before taking emission data, the filament *F* was aged by running it at a suitable temperature for 15 to 24 hours. The tube was then immersed in liquid air and the filament flashed again at a very high temperature for about a minute. The temperature of the filament was then lowered to the desired value and emission data taken at different anode voltages. Before taking data at any other temperature the flashing at high temperature was usually repeated.

It is evident that under these conditions the surface of the cathode was quite free from adsorbed gas. The calcium surface at liquid air temperatures maintained an excellent vacuum and it was found that emission data taken under these conditions were satisfactorily reproducible not only on the same tube but on samples of the same wire made up in different tubes.

TEMPERATURE SCALES

The temperature scale for tungsten at temperatures above 1200°K has been derived by Langmuir[4] and also, more recently, by Worthing and Forsythe.[3] In view of the extremely accurate determinations made by the latter of the values of the different factors involved, the temperature scale established by them has been adopted in the present connection.

According to this scale, the energy radiated by tungsten as a function of the absolute temperature is given in watts per cm^2 by the relation.

$$\log_{10}E = 3.680(\log_{10}T - 3.3) - (1040/T) + 1.900 \,. \tag{5}$$

In the determination of temperatures for any given sample of wire a vacuum lamp was made up with a V-shaped filament, and after suitable ageing this lamp was pyrometered against a standard lamp furnished by Worthing and Forsythe, using light of wave-length 0.665μ. In this manner a relation was obtained between the filament current F_i and the absolute temperature. A number of the lamps containing filaments from the same sample of wire as that used for electron emission measurements were also sent to Dr. Forsythe for check determinations on the relation between temperature and filament current. The relation between log F_i and log T was then plotted on a large scale so that interpolation could be made quite accurately. It may be observed in this connection that the pyrometry data obtained in this laboratory and by Dr. Forsythe on pure tungsten filaments were found to be in splendid agreement with the temperatures calculated by means of Eq. (5) from the energy radiated, after a correction had been made for the lead losses (see subsequent section).

In the case of molybdenum, a vacuum lamp containing a sample of the wire used for electron emission work was also pyrometered by Dr. Forsythe. The temperature scale used depends upon some recent determinations of the emissivity ot molybdenum for $\lambda 0.665\mu$, according to which this metal is less like a black body than tungsten.

Regarding the temperature scale for tantalum, there are much less accurate data available than in the case of tungsten. The current-temperature relation for the wire used was obtained by pyrometering a vacuum lamp against the standard tungsten lamp mentioned already.

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[4] Langmuir, Phys. Rev., **7**, 302 (1916)

The true temperature of the tantalum was then derived from that of the tungsten at the same brightness by the relation,

$$\frac{1}{T}-\frac{1}{S}=\frac{\lambda \log_e E_\lambda}{C_2} \qquad (6a)$$

where S = brightness temperature;

T = true temperature;

E_λ = emissivity for wave-length λ;

$C_2 = 14{,}350$ microns × deg. K.

For any two substances at the same brightness temperature it follows that

$$\frac{1}{T'}-\frac{1}{T''}=\frac{\lambda \log_e (E'_\lambda / E''_\lambda)}{C_2}\,. \qquad (6b)$$

Data on the emissivity of tantalum have been published by Foote and Fairchild.[5] The emissivity for λ 0.65μ is given as 0.60 at $T=1373$, and 0.48 at $T=2873$°K. On the other hand, Dr. Worthing finds as a result of some recent determinations that at approximately all temperatures, E_λ for tantalum is $1.088 \times E_\lambda$ for tungsten.[6] Using these data and those for tungsten published by Worthing[7] we obtain the following equivalent brightness temperatures for the two metals. The second column gives the temperatures calculated on the basis of Foote and Fairchild's values of E_λ, while the third column gives the temperatures calculated by means of Worthing's values, which are those used in the present investigation.

Corresponding true temperatures for equivalent brightness

Tungsten	Tantalum	
	(F. & F.)	(W)
1200	1180	1194
1400	1375	1392
1600	1570	1590
1800	1765	1788
2000	1960	1984
2200	2155	2181
2400	2350	2378

Corrections for Lead-Loss

It is obvious that in order to calculate electron emission per unit area from the emission observed for any given filament, a correction must be applied for the fact that the temperature along a filament decreases to practically room temperature as the lead is approached.

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[5] P. D. Foote and C. O. Fairchild, Trans. Am. Inst. Mining Eng. 1919, p. 1389.

[6] Personally communicated to the writers.

[7] A. G. Worthing, Phys. Rev. **10**, 377 (1917); Trans. Am. Inst. Min. Eng. 1919, p. 1895.

Corrections for the cooling effect of the leads have been derived by Langmuir,[8] and are expressed by the following relations.

When the ends of a V-shaped filament are cooled by large leads, the voltage correction for the two ends, that is the decrease in voltage due to the cooling effect of the leads, is

$$\Delta V = .00026\,(T-400)\text{ volts .} \tag{7}$$

But the cooling also affects the electron emission, and the correction for this is

$$\Delta V_H = 2(0.00017T\phi - 0.05)\text{ volts .} \tag*{(8)*}$$

Here ΔV_H represents the voltage of a length of uncooled filament which would give the same effect as the *decrease* caused by the cooling of the leads. In this equation ϕ is a number which depends upon the temperature coefficient of the quantity H which may represent any property of the metal, such as electron emissivity, candlepower, etc. If we let n represent the exponent of the power of the temperature with which H increases, then the values of ϕ depend upon n as follows;

$n=0.5$	1.0	2	2.5	5	10	20	30	50
$\phi=0.48$	0.85	1.23	1.44	1.72	2.10	2.47	2.69	2.95

For the case of electron emission,

$$n = d\log I/d\log T = 2 + b_0/T\ . \tag{9}$$

Thus, corresponding to any values of b_0 and T, a value of ϕ is obtained and from this ΔV_H can be calculated.

Formulas for the end-loss corrections have also been derived by Worthing.[9] That for ΔV (correction for energy input) agrees substantially with that derived by Langmuir and is

$$\Delta V = 1.00\sqrt{2\rho\eta}/Q\ . \tag{10}$$

In this equation ρ is the resistivity, η the radiation intensity and Q a function of the maximum temperature. The correction for electron emission varies with the value of b_0. For tungsten (and the same correction may be applied to tantalum and molybdenum) the correction as given by Worthing is

$$\Delta V_H = 3.85\sqrt{2\rho\eta}/Q\ . \tag{11}$$

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[8] I. Langmuir, Phys. Rev. **7**, 151 (1916);
Gen. Elec. Rev. **19**, 210 (1916);
Trans. Far. Soc. **17**, part 3, 2 (1921)

* In a paper published by S. Dushman and Jessie Ewald (General Electric Review, **26**, 154, 1923) the factor 2 in this equation was omitted.

[9] A. G. Worthing, J. Franklin Inst. 597 (1922)

This equation gives practically the same results as Eq. (8) for values of T below about 2400°K, but gives much greater corrections for higher temperatures.

If now i_{obs} represents the actually observed electron emission, the corrected emission i_{cor} for the total area of the filament is given by the relation

$$i_{cor} = i_{obs} \times (V + \Delta V)/(V + \Delta V - \Delta V_H) \ . \tag{12}$$

In the following tables this correction factor is denoted by f.

Inadvertently the factor 2 in Eq. (8) was omitted by Dr. Langmuir in his paper. Since his was the relation used by the writers for calculating f and the corrected emission per unit area, it is evident that the values of b_0 thus obtained are slightly higher than those obtained by means of Worthing's relation. However, as the difference amounts, in the case of the filaments discussed in the present paper, to an increase in the calculated value of b_0 of not more than 125 (about 1/4 per cent of the value of b_0) it may be neglected in comparison with the effect of other experimental errors.

CORRECTION FOR SCHOTTKY EFFECT

In measuring the electron emission from any filament it is observed that the actual value of the emission increases gradually with the anode voltage, even when the current is considerably below the limit due to space charge.

W. Schottky pointed out[10] in 1914 that, owing to the influence of the "electric image," the electron emission must increase with the field strength at the cathode in accordance with the following relation

$$i_v = i_0 \epsilon^{(4.39/T)(dV/dx)^{\frac{1}{2}}} \tag{13}$$

where i_v = electron current at anode voltage V:
i_0 = electron current at zero field strength:
dV/dx = voltage gradient at the cathode.

Since the fundamental Eq. (1) for electron emission was derived on the assumption that there is no field gradient at the cathode it is obviously necessary to correct the actually observed emission data for this affect.

In the case of a filament of radius r along the axis of a cylindrical anode of radius R,

$$\frac{dV}{dx} = \frac{V}{r \log (R/r)} \ . \tag{14}$$

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

For most of the tubes used in connection with the present investigation it is difficult to calculate the value of dV/dx accurately. However, the magnitude of the exponential factor in Eq. (13) can be obtained by actually measuring the emission for a range of anode voltages. Writing this equation in the form

$$\log_{10} i_v = \log_{10} i_0 + (4.39/2.303T)\sqrt{dV/dx}$$

it is evident that if log i_v is plotted against $\sqrt{V}$ a straight line should be obtained, and the following relation should exist

$$2.303\, T \frac{\Delta \log_{10} i}{\Delta\sqrt{V}} = 4.39\sqrt{s} \qquad (15)$$

where s is a *constant* for any tube and depends upon the geometrical arrangement of the electrodes. Thus, if Schottky's equation is valid, it ought to be observed that $T\ \Delta \log i/\Delta\ \sqrt{V}$ is a *constant* for any tube. Furthermore, by means of the value of $\Delta \log i/\Delta\sqrt{V}$ thus obtained it is evidently possible to calculate i_0, the emission that would be obtained if there were no field gradient at the cathode.

Eqs. (1) and (15) can be combined in the form

$$I_v = A T^2 \epsilon^{-(b_0 - \Delta b_0)/T} \qquad (16)$$

where

$$\Delta b_0 = 4.39\sqrt{dV/dx} = 4.39\sqrt{Vs} = 2.303\, T(\Delta \log_{10} i/\Delta\sqrt{V})\sqrt{V}. \qquad (17)$$

That is, for any tube, the value of Δb_0 varies as $\sqrt{V}$.

EMISSION DATA FOR TUNGSTEN

In the following tables, the data are given from which values of I and b_0 were calculated. F_i denotes the filament amperes, and F_v the filament volts. From measurements of the electron current at different anode voltages, a value of $T\Delta\log_{10} i/\Delta\sqrt{V}$ was obtained, and from the average of these values for all the temperatures a corrected value of $\Delta \log_{10} i/\Delta\sqrt{V}$ was obtained, which was then used to calculate i_0.

The value of the lead-loss correction factor was calculated as described in a previous section, from the filament potential drop and the pyrometered value of T. The value of I, the emission in amp./cm^2, was then obtained by the relation

$$I = i_0 \times f/\text{area}.$$

Data obtained with several tubes are given in detail in the following tables. Specially prepared pure tungsten was used in order to avoid any effects due to slight traces of impurities.

TABLE I

Results for pure tungsten filament, in tube 107-1

Weight of wire = 1.517 mg/cm; diameter = 0.01003 cm; total length of filament = 15.0 cm; area = 0.474 cm²

F_i	F_v	T	Anode volts	i	$T\frac{\Delta\log_{10}i}{\Delta\sqrt{V}}$	$\left(\frac{\Delta\log_{10}i}{\Delta\sqrt{V}}\right)_{cor}$	$\log_{10}i_0$ +8	i_0
0.550	3.98	1470	475	1.95×10^{-8}				
			400	1.89				
			225	1.75				
			100	1.61	10.29	0.00728	0.1310	$1.35\ \times10^{-8}$
0.608	4.68	1543	475	1.240×10^{-7}				
			400	1.195				
			225	1.110				
			100	1.020	10.51	0.00693	0.940	$8.71\ \times10^{-8}$
0.688	5.74	1640	475	1.080×10^{-6}				
			400	1.050				
			225	0.970				
			100	0.905	10.66	0.00653	1.889	7.745×10^{-7}
0.792	7.22	1761	475	1.160×10^{-5}				
			400	1.120				
			225	1.040				
			100	.975	11.09	0.00608	2.929	8.492×10^{-6}
0.912	9.12	1897	475	1.065×10^{-4}				
			400	1.040				
			225	0.975				
			100	0.910	10.21	0.00563	3.903	7.998×10^{-5}
1.065	11.77	2065	475	1.150×10^{-3}				
			400	1.124				
			225	1.060				
			100	0.996	10.95	0.00518	4.9465	8.841×10^{-4}
1.235	15.30	2239	475	1.154×10^{-2}				
			400	1.124				
			225	1.050				
			100	0.984	11.20	0.00478	5.9155	8.231×10^{-3}

TABLE II

Values computed from data in Table I.

T	$10^3/T$	$V+\Delta V$*	$V+\Delta V$ $-\Delta V_H$*	f*	$\log I$ +8	$\log(I/T^2)$ +14	b_0	T (calc.)
1470	0.6803	4.22	3.30	1.275	0.5606	0.2260	52,600	1472
1543	.6482	4.94	3.95	1.25	1.3614	0.9848	52,580	1546
1640	.6098	6.02	4.94	1.215	2.2978	1.8682	52,530	1644
1761	.5679	7.54	6.34	1.19	3.3280	2.8366	52,480	1765
1897	.5271	9.47	8.12	1.167	4.2949	3.7387	52,590	1897
2065	.4842	12.17	10.64	1.143	5.3296	4.6996	52,710	2062
2239	.4467	15.75	14.03	1.122	6.2900	5.5900	52,520	2244
						Average:	52,580	
						Value from slope in log (I/T^2) vs $(1/T)$:	52,560	

* Calculated by means of Eqs. (10) and (11). As mentioned previously the values of b_0 calculated by use of Langmuir's uncorrected relation for ΔV_H lead to values of b_0 which are about 1/4 percent higher.

The average value of $T\Delta\log_{10}i/\Delta\sqrt{V}$ was 10.70. From this the corrected value of the slope $\Delta\log_{10}i/\Delta\sqrt{V}$ was derived as given in Table I. In Fig. 2, values of $\log_{10}i_v$ for each temperature are plotted against those of $\sqrt{V}$. The ordinates give the increase in $\log_{10}i_v$ as compared with $\log_{10}i_0$. The latter was obtained by drawing a straight line with the corrected slope through as many of the points as possible. The actual values of $\log_{10}i_0$ are given in Table I. It will be observed that within the limits of experimental accuracy $T\Delta\log_{10}i/\Delta\sqrt{V}$ is constant.

As shown in Table II, the values of b_0 are remarkably constant although the actual electron emission values vary over a range of 500,000: 1 and the extreme temperatures are as 1.52:1.

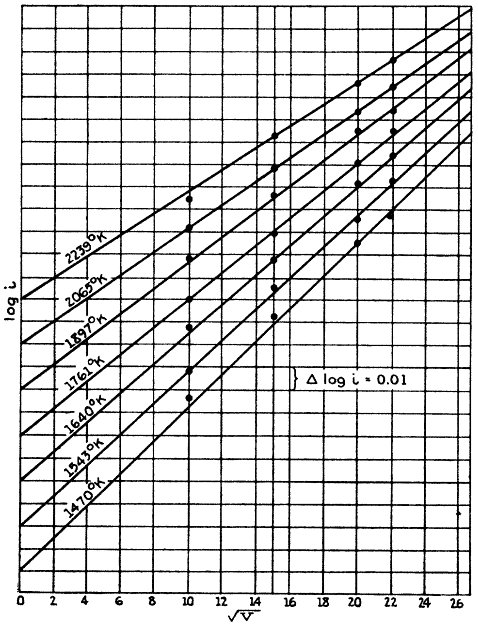

Fig. 2. Variation in emission with anode voltage.

An additional test of the validity of Eq. (1) is furnished by plotting log (I/T^2) against $1/T$ as shown in Fig. 3. The slope of the best straight line through all the points as obtained by the method of least squares (see subsequent section) corresponds to a value $b_0=52{,}560$, which is practically identical with that obtained as the average value in Table II.

The last column in this table gives the value of T calculated for the given value of log I on the basis $b_0=52{,}600$, which, as is pointed out more fully in a subsequent section, we believe to be the best value for tungsten.

The agreement between these two sets of values must be regarded as very satisfactory.

TABLE III

*Results for pure tungsten filament, in tube 107-2**

T	$10^3/T$	$\log I+8$	$\log (I/T^2)+14$	b_0	T(calc.)
1477	0.6770	0.6065	0.2677	52,760	1475
1543	.6482	1.3432	0.9666	52,620	1543
1640	.6098	2.2850	1.8554	52,570	1641
1761	.5679	3.3158	2.8248	52,520	1764
1897	.5271	4.2696	3.7134	52,690	1895
2065	.4842	5.3043	4.6743	52,790	2057
2239	.4467	6.2659	5.5659	52,640	2239
			Average	52,660	
			Value from slope	52,570	

* This filament was from the same wire as in tube 107-1

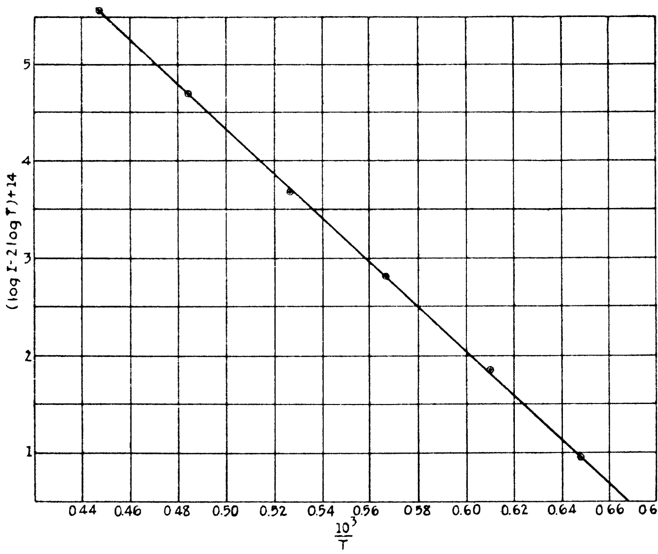

Fig. 3. Variation in emission from tungsten with temperature; b_0 from slope=52,560.

In the case of tube 54, the sample of pure tungsten wire used was from a different metal lot from that used in the other tubes. The average value of b_0 is 52, 710, with a maximum of 52,880 and minimum of 52,410. From the slope of log (I/T^2) against $1/T$, $b_0=52{,}000$. This series of data was, however, not quite as reliable as the other series given above.

In the case of tube 162-2, the tungsten wire used was a sample of unthoriated wire such as is used in regular lamp production. In order to obtain a comparison with the specially pure tungsten wire used in obtaining the previous data, two similar V-shaped filaments were inserted in the tube, one of the specially pure wire and the other of the regular wire. Thus emission data were obtained under identical conditions of vacuum. In taking emission data from either filament the other filament was connected to the negative end of the heated filament. The data for the specially pure tungsten filament used in this tube have been given already in Table IV. Table V gives the results obtained with the regular wire. The value of b_0 obtained from the slope by the method of least squares is 51,390 (see Fig. 5). The difference between this and the average value 52,470 is probably due to some slight trace of impurity in the wire.

TABLE IV

*Results for pure tungsten filament, in tube 162**

T	$10^3/T$	$\log I+7$	$\log(I/T^2)+14$	b_0	T calc.
1533	0.6524	0.1750	0.8040	52,890	1525
1653	.6049	1.3492	1.9126	52,810	1650
1770	.5649	2.3238	2.8278	52,790	1765
1884	.5308	3.1521	3.6019	52,840	1877
1993	.5017	4.8592	4.2600	52,890	1985
2101	.4760	5.4992	4.8544	52,830	2095
2204	.4537	6.0593	5.3792	52,830	2200
			Average	52,830	
			Value from slope (Fig. 4)	52,860	

* The filament in this tube was from the same wire as that in tube 107-1.

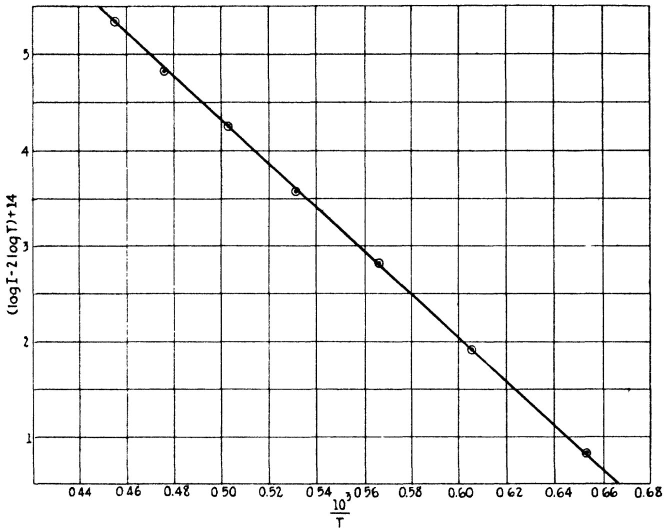

Fig. 4. Variation in emission from tungsten with temperature. $b_0=52,860$.

Emission data were also taken on a sample of regular unthoriated wire obtained from another metal lot. In this case the average value of b_0 was 52,950.

TABLE V

Results for commercial unthoriated tungsten filament, in tube 162-2.

T	$10^3/T$	$\log I+7$	$\log (I/T^2)$ $+13$	b_0	T(calc.)
1535	0.6515	0.4036	0.0314	52,140	1550
1621	.6169	1.1892	0.7696	52,300	1632
1702	.5876	1.9094	1.4476	52,250	1715
1786	.5599	2.4982	1.9944	52,580	1787
1868	.5353	3.0875	2.5447	52,610	1867
1946	.5146	3.6011	3.0229	52,710	1946
2020	.4950	4.0701	3.4593	52,670	2017
2090	.4785	4.4962	3.8560	52,550	2091
2159	.4633	4.8736	4.2052	52,550	2162
2225	.4493	5.2579	4.5631	52,370	2235
			Average	52,470	
			Value from slope (Fig. 5)	51,390	

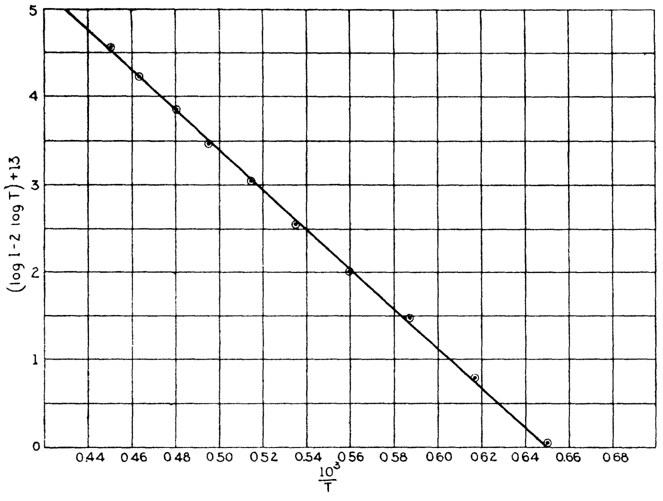

Fig. 5. Emission data for commercially pure tungsten; $b_0=51,390$.

In order to obtain data which would be free from lead loss correction, a tube (No. 79) was made up similar in size to that described already, but with a filament along the axis and with guard rings of quartz put in so that on evaporating the calcium the anode would consist of three portions not connected electrically. The central part was made 10 cm long, while each of the guard ring anode portions was about 5 cm in length. Pure tungsten wire was used, from the same lot as for tube 107-1. The data obtained in this case are given in Table VI.

Some further measurements were carried out with a sample of unthoriated tungsten in which the crystals were very long. This was prepared by special treatment and it appeared of interest to determine in this case the effect of crystalline structure on the emission. The average value of b_0 obtained for four different temperatures was 52,400, which may be considered as in very good agreement with the values obtained for the regular wire.

TABLE VI

Results for pure tungsten wire in special tube 79.

T	$10^3/T$	$\log I+5$	$\log (I/T^2)+11$	b_0	T(calc.)
1810	0.5524	0.6118	0.0964	52,860	1803
1930	.5180	1.4971	0.9259	52,690	1928
2000	.5000	1.9733	1.3714	52,550	2002
2090	.4785	2.4720	1.8318	52,710	2087
2170	.4608	2.9325	2.2595	52,580	2172
			Average	52,680	
			Value from slope	53,850	

Value of b_0 for tungsten. Summarizing the values of b_0 obtained in all the above series of measurements it will be observed that the maximum value obtained was 52,950, and the minimum, 52,400. The most reliable measurements gave values ranging around 52,600.

It is evident that in a determination of b_0 as carried out in this investigation, there are many possible sources of error. First, pyrometric data were never determined for the actual filament in the tube, but for a sample of the same wire in a vacuum lamp. Now while the actual temperature for a given filament current can be measured on the same filament with a high degree of accuracy (2 to 3 degrees at 2000°K) such accuracy is difficult to obtain where two samples are made up in different lamps. Slight variations in the ageing schedule will alter the emissivity at a given wave-length, and there is no doubt that in many cases the differences between the pyrometered values of T and those calculated from the electron emission on the basis $b_0 = 52{,}600$ are to be ascribed to this cause.

It is to be observed in this connection that a 1 per cent error in T causes approximately the same error in the calculated value b_0. Hence an error in pyrometry of 10 degrees at $T = 2000$ would lead to an error of 0.50 per cent in that of b_0.

There is, furthermore, some uncertainity as to the exact magnitude of the lead loss correction. From Eq. (9) it follows that an error of 5 per cent in the determination of I leads to an error of approximately 0.2 per cent in the value of b_0. Such an error was quite possible with the lengths of filaments used when it is considered that both Langmuir's and Worthing's formulas for lead loss correction assume that the leads are maintained at room temperatures.

In addition, account must be taken of the fact that in order to obtain accurate emission data from a filament, the latter must be flashed for a considerable time to get rid of residual traces of adsorbed oxygen. As has been shown by Langmuir even a very low pressure of this gas increases the value of b_0 enormously. This effect is much more pronounced at lower temperatures where the rate of evaporation of oxygen is low.

In view of these considerations it would be reasonable to conclude that the lower values of b_0 are the more reliable, and that the best value for tungsten is 52,600, with an error of ± 250 (corresponding to an estimated error of 0.5 per cent in the determination of temperature). The agreement between the pyrometered values of T and the values calculated from I on this basis tends to confirm this conclusion.

Emission Data for Molybdenum

Regular molybdenum wire (0.0129 cm in diameter) was used in the form of V-shaped filaments. As mentioned previously, pyrometer data were determined for us by Dr. Forsythe, on a vacuum lamp containing a filament of the same wire. In the following table only the essential data are given and details regarding corrections for lead loss and the Schottky effect have been omitted.

Tube No. 54. Length of filament = 10 cm. Data obtained with this tube are given in Table VII. The value of b_0 from the slope of log (I/T^2) against $1/T$ is 52,770, while the average value of b_0 is 50,230. However the emission data, especially at lower temperatures, were not very constant. Probably there was a residual gas effect in this tube.

Table VII

Results for molybdenum filament in tube 54.

T	$10^3/T$	$\log I + 8$	$\log(I/T^2)+14$	b_0	T (calc.)
1438	.6954	0.8260	0.5106	50,560	1425
1502	.6658	1.4538	1.1004	50,790	1480
1553	.6440	2.4786	1.6610	50,490	1536
1599	.6254	2.4786	2.0708	50,490	1585
1643	.6087	2.8891	2.4579	50,400	1632
1685	.5934	3.2618	2.8086	50,330	1675
1728	.5788	3.5916	3.1166	50,390	1717
1890	.5291	4.8195	4.2665	50,100	1885
1930	.5181	5.1173	4.5461	49,910	1930
1968	.5081	5.3704	4.7822	49,860	1965
2006	.4985	5.5922	4.9876	49,850	2012
2045	.4890	5.7995	5.1815	49,730	2050
			Average	50,230	
			Value from slope	52,770	

Tube No. 167. Length of filament = 14.85 cm. Data obtained with this tube are given in Table VIII. The agreement between the average value of b_0 and that derived from the slope (51,180) is only fair . There was no evidence of residual gas effects in this tube and the data were very constant.

TABLE VIII

Results for molybdenum filament in tube 167

T	$10^3/T$	$\log I+7$	$\log (I/T^2)+14$	b_0	T(calc.)
1466	0.6821	0.3020	0.9696	50,010	1466
1599	.6253	1.6577	2.2499	49,830	1600
1685	.5934	2.3923	2.9391	49,800	1690
1849	.5409	3.6418	4.1080	49,690	1860
2006	.4985	4.6500	5.0456	49,630	2023
2116	.4726	5.2880	5.6370	49,410	2140
			Average	49,730	
			Value from slope	51,180	

Value of b_0 for molybdenum. It will be observed that the values of b_0 consistently decrease with increase in T, and that the average value obtained by means of Eq. (4) is less than that obtained from the slope. On the other hand, the difference between the latter values (1,590) is greater than that between the maximum (50,560) and minimum (49,410) values calculated by means of Eq. (4).

These results can be accounted for as due to the presence on the surface of the filaments of adsorbed layers of oxygen. The amount of this adsorbed gas decreases with increase in temperatures and, therefore, causes a decrease in the values of b_0. Furthermore, the amount of adsorbed gas must depend on the exact ageing schedule and other factors in the previous history of the tube. This would account for the difference observed between the values of b_0 in the two tubes. Thus the surface of the filament in tube 167 must have been more free from contamination than that used in 54.

Observations with other tubes containing molybdenum filaments were in agreement with the conclusion that in the case of this metal, it is difficult to obtain emission data on absolutely clean surfaces; average values of b_0 were obtained ranging from 50,900 to 49,700 for different samples, with individual variations in any set of observations which were considerably greater than those shown in either Table VII or Table VIII.

It would, therefore, seem logical to conclude that the lowest values of b_0 are probably the most accurate. On the other hand, the temperature scale for molybdenum is not known with anywhere near the same degree of accuracy as that for tungsten, and this may account to some extent for the differences between the values of b_0 obtained by applying Eq. (4) and those obtained from the slope.

In view of these considerations, it is evident that the results obtained for this metal cannot be regarded as evidence either for or against the validity of Eq. (4). Tentatively the writers believe that there is justification for assuming that the emission from molybdenum may be represented (as accurately as the data permit) by the parameters $\log A = 1.779$ and $b_0 = 50{,}000$. From the maximum and minimum values given in Tables VII and VIII, it would also appear that the maximum deviations are approximately ± 500.

EMISSION DATA FOR TANTALUM

The temperature scale for tantalum has been discussed in a previous section. Two different samples of wire were used. The first came from Germany (Osram Co.) about ten years ago, and was, therefore, the same kind of material as was used in the tantalum lamp of about 1910-11; the second sample was obtained from the Fansteel Co., Chicago.[11]

As in the case of molybdenum, the oxide of tantalum is quite nonvolatile and the filaments must, therefore, be heated to as high a temperature as possible (2400°K) in vacuum in order to obtain thoroughly clean surfaces. Furthermore, it has been found desirable in the preparation of the filaments, not to arc weld them to the leads in hydrogen (as is customary with tungsten) but to spot-weld the joints. As is well known, tantalum at higher temperatures absorbs hydrogen, and on subsequent flashing in vacuum, there is not only considerable evolution of gas, but also apparently a disintegration of the filament so that the glass walls became blackened with the deposited metal.

Before taking emission data on the evacuated tubes, the filaments were aged for a number of hours at 2200° to 2400°K until the cold resistance remained constant. It should be observed that occluded gases increase the resistance of tantalum, so that the measurement of this property forms a guide to the degree of evacuation of the wire.

Osram wire (Tubes No. 269, 270 and 271). The data on the three tubes made up with this wire were so similar that only those obtained with one of these (No. 271) are given in Table IX. The wire used was 0.222 mm (8.75 mil) in diameter, and the total length of the filament was 15.1 cm, corresponding to an area of 1.055 cm^2. The measurements on the Schottky effect gave for the slope $T\Delta \log i\Delta/\sqrt{V}$ the average value

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[11] See C. W. Balke, Ind. Eng. Chem. **15**, 560 (1923) for full description of the properties of this material.

7.36, corresponding to $\Delta b_0 = 170$ for 100 volts on the anode. As shown in Fig. 6, the agreement between the value of b_0 from the data in Table IX and that from the slope of log (I/T^2) against $(1/T)$ is fair.

TABLE IX

Results for Osram tantalum filament, in tube 271

T	$10^3/T$	$\log I + 6$	$\log(I/T^2) + 13$	b_0
1482	0.6747	0.2565	0.9147	47,320
1586	.6304	1.1091	1.7083	47,740
1718	.5821	2.1448	2.6748	47,870
1798	.5560	2.7315	3.2217	47,940
1872	.5342	3.2498	3.7052	47,710
1978	.5055	3.8989	4.3063	47,690
2048	.4883	4.2943	4.6717	47,670
			Average	47,700
			Value from slope	46,840

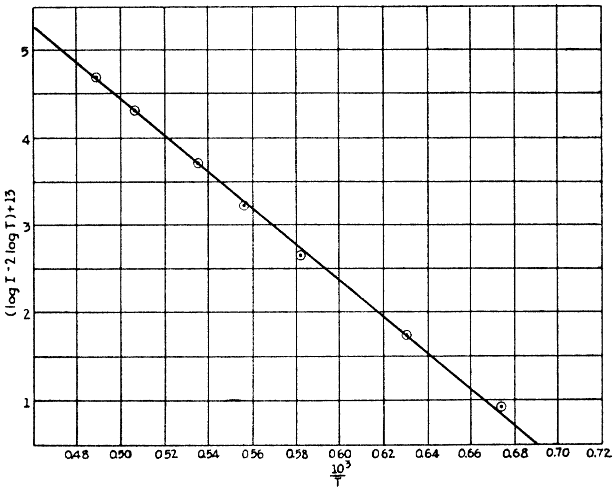

Fig. 6. Plot of emission data for tantalum; $b_0 = 46{,}840$.

Fansteel wire (Tubes No. 267, 268). The data on these two tubes also showed very good agreement. The wire used was 0.254 mm (9.9 mil) in diameter and had a total length of 15.0 cm (area = 1.19 cm^2). The correction for the Schottky effect was found to be the same as for the other tantalum filaments. Table X gives the results obtained with this wire.

Value of b_0 for tantalum. The agreement between the values of b_0 obtained for the two different samples of tantalum may be regarded as very satisfactory, and we have, therefore, taken as an average, the value

$b_0 = 47{,}800 \pm 500$. The accuracy is probably not much better than within one per cent, since the temperature scale has not been determined as accurately as in the case of tungsten.

TABLE X

Results for Fansteel tantalum filaments.

T	$10^3/T$	$\log I + 7$	$\log(I/T^2) + 13$	b_0
1450	0.6896	0.8094	0.4866	47,720
1562	.6401	1.7880	1.4006	48,140
1676	.5967	2.7517	2.3031	48,170
1746	.5728	3.2988	2.8148	48,090
1848	.5412	4.0006	3.4672	48,140
1904	.5252	4.3980	3.8386	48,000
1964	.5091	4.7601	4.1737	48,000
2022	.4945	5.0904	4.4788	47,600
			Average	48,000
			Value from slope	47,550

VALUE OF CONSTANT A

The results discussed in the previous sections show that for tungsten and tantalum, the value of A is the same, within the limits of experimental errors, and corresponds to that given by the Sackur Tetrode theory, that is, 60.2 amp. cm^{-2} deg^{-2}. This conclusion was reached by finding that in the large majority of cases, the individual values of b_0 calculated from observations at different temperatures by means of Eq. (4) were in agreement with the values obtained by plotting log (I/T^2) against $1/T$.

In the case of molybdenum, as stated previously, the evidence for the validity of the value $\log A = 1.779$ is not so good. On the other hand, since there is a possible explanation of this discrepancy, it cannot be stated that the observations obtained in this case are in definite disagreement with equation (4).

As a check on the validity of Eq. (4), the values of log A and b_0 were calculated for each set of data by the method of least squares. Table XI gives a summary of the values thus obtained. In a recent paper N. Campbell[12] has advocated the use of the so-called method of "zero sum." The values of log A and b_0 calculated in this manner are given in the last two columns.

Undoubtedly the most accurate data are those given in Tables II, III and IV. The values of log A obtained from these data are so nearly the same as the theoretical value 1.779 that the difference must be ascribed to experimental errors in temperature determination.

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[12] N. Campbell, Phil. Mag. **47**, 816 (1924)

While the data for tantalum and (much more so) those for molybdenum are not in as good agreement with Eq. (4) as those for tungsten, the writers believe that there are two possible causes for these differences: (1) Insufficient knowledge of the radiant emissivity of these metals as a function of the temperature, and (2) the practical difficulty in obtaining absolutely clean surfaces free from adsorbed oxygen.

TABLE XI

Average Values of b_0 and of log A

Metal	Table	ByEq.(4)	Least square method		Zero sum method	
		b_0	b_0	$\log_{10}A$	b_0	$\log_{10}A$
Tungsten	II	52,580	52,560	1.773	52,500	1.759
	III	52,660	52,570	1.753	52,450	1.725
	IV	52,830	52,860	1.787	52,740	1.757
	V	52,470	51,390	1.532	51,540	1.566
	VI	52,680	53,850	2.034	53,910	2.047
	Averages:	52,640	52,650	1.776	52,630	1.771
Molybdenum	VII	50,230	52,770	2.404	52,700	2.385
	VIII	49,730	51,180	2.133	51,130	2.120
	Averages:	49,980	51,980	2.268	51,920	2.252
Tantalum	IX	47,700	46,840	1.567	47,350	1.693
	X	48,000	47,550	1.663	48,040	1.785
	Averages:	47,850	47,200	1.615	47,700	1.744

In view of these considerations, it has seemed best to adopt, for the present, the mean values of b_0 derived by means of Eq. (4), although it is quite possible that the emission from molybdenum actually is not in accord with this equation.

Initially it was concluded that the same constant A ought to be valid for electron emission data from all substances. Preliminary investigations with thoriated filaments seemed to be in agreement with this conclusion, but more careful observations by Dr. K. H. Kingdon and also by the writers, have shown that for these filaments, the value of A is smaller and varies with the amount of the surface covered by thorium.

Furthermore the observations of K. H. Kingdon on caesiated tungsten filaments and published data on the emission from oxide coated filaments, lead to the conclusion that for *coated filaments* the value of the constant A may be either greater or lower than both the values derived from Eq. (2) and (3). By coated filaments we mean all filaments in which the emission is due to, or is affected by, a surface layer. Thus an adsorbed layer of oxygen atoms on the surface of tungsten lowers the emission enormously, and as Kingdon has shown, while the value of A is much greater than for pure tungsten, the value of b_0 is also increased considerably.

An explanation for this apparent discrepancy between the theoretical and observed values of the constant A has been suggested by I. Langmuir and L. Tonks.*

As pointed out by P. W. Bridgman,[13] the latent heat of evaporation of electrons consists of two portions, that corresponding to the energy which would be absorbed at constant surface charge, and a heating effect due to the appearance of a positive charge on the surface (surface heat). It is only when this surface heat is zero that A has the value derived from the Third Law of Thermodynamics and given by Eq. (2) or (3). Thus the fact that the value of A actually observed for tungsten is in accord with Eq. (4) may be taken as indicating that for that metal at least the surface heat is negligibly small.[14]

It is of interest in this connection to point out that apparently the effect of monatomic layers of various substances on the value A varies according to whether the atoms composing this layer are electropositive or electronegative. Thus oxygen increases the value of the constant. In fact for a layer of oxygen on tungsten, Kingdon[15] obtains the value $A = 5\times 10^{11}$. On the other hand, in the case of electropositive atoms, such as thorium and caesium on tungsten, the values of A are considerably lower. According to Kingdon, the values of A for thorium is about 7 (and independent experiments by the writers give results in agreement with this value). For caesium the value is less than 0.003.†

Similarly, in the case of platinum filaments coated with oxides of the alkaline earths, A is very high, approaching that of oxygen on tungsten. The writers are obtaining more data on this subject in the hope that some general relations will be obtained between the nature of the monomolecular layer and the effect on the value of A.

DISCUSSION OF PREVIOUS DATA ON EMISSION FROM TUNGSTEN, MOLYBDENUM, AND TANTALUM

Tungsten. According to Langmuir's[16] earlier investigation, the constant A (Richardson's equation) is given as 2.36×10^{7} amp. cm^{-2} $\text{deg}^{-1/2}$, while b is given as 52,500. The temperature scale for tungsten as used by Langmuir at that time is somewhat different from that used in the present paper. Thus 2000°K on Langmuir's scale of 1913 corresponds

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* A discussion of this theory will appear in the near future.

[13] P. W. Bridgman, Phys. Rev. **14**, 325 (1919)

[14] See also a recent paper by H. A. Wilson, Phys. Rev. **23**, 38 (1924)

[15] K. H. Kingdon, Phys. Rev. **24**, 510 (1924)

† The high value of log A obtained for molybdenum (see Table XI) may probably be explained in the same manner as due to adsorbed oxygen.

[16] I. Langmuir, Phys. Rev. **2**, 402, 450 (1913)

to 2016°K on the present scale. At this temperature, the emission according to Langmuir is .0042 amp. cm^{-2}, while on the basis of the value $b_0=52{,}600$, the emission is .0042 amp. cm^{-2} at $T=2115$°K. To account for Langmuir's observed emission at $T=2016$°K, we would have to assume $b_0=50{,}000$ approximately. This is much lower than any of the values obtained in the present investigation. The difference is probably due to the presence in Langmuir's samples of slight traces of some more active emittor, such as thoria, alkali, or alkaline earth. In fact, the writers have obtained samples of tungsten which were substantially free from all active additions, and which, nevertheless, showed abnormally high electron emission for quite a long period.

The same reasons undoubtedly account for the rather high emission observed by K. K. Smith[17] for one sample of tungsten. Assuming the correctness of his temperature scale, the emission data recorded on p. 811 of his paper give a value for b_0 of 51,700. On the other hand, the data given on p. 820 of the same paper correspond to a value for b_0 of 56,000 (from the slope of log (I/T^2) against $1/T$). This high value of b_0 was most probably due to the presence of adsorbed gas on the surface of the filament.

The most recent measurements of the emission from tungsten are those obtained by C. Davisson and L. H. Germer.[18] As shown in the paper by S. Dushman,[1] these data are in excellent agreement with Eq. (4). The average value of b_0 is 51,860. As the anode voltage was 196, it is necessary to correct this value for the Schottky effect. From the description of the tube used in the investigation, it is reasonable to conclude that for $V=0$, the value of b_0 would have been $51{,}860+500=52{,}360$ approximately.

Molybdenum. Langmuir[16] gives for molybdenum the values $A_1=2.1\times10^7$ amp. cm^{-2} $\text{deg.}^{-\frac{1}{2}}$ and $b=50{,}000$. Hence, at $T=2000$, $I=0.013$ amp. cm^{-2}, while on the basis of Eq. (4), using the value $b_0=50{,}000$, we obtain the result $I=0.0033$ amp. cm^{-2} at that temperature. Probably the difference in the temperature scales used in the two investigations and differences in the state of the surface account for this difference in emission data.

Stoekle[19] has obtained the values $A_1=11\times10^7$ and $b=53{,}600$, but there is some doubt as to whether his results were not affected by the presence of gas.

Tantalum. Langmuir[16] gives for this metal the values $A_1=1.12\times10^7$ amp. cm^{-2} $\text{deg.}^{-1/2}$ and $b=50{,}000$. Converting to Eq. (4) we obtain for

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[17] K. K. Smith, Phil. Mag. **29**, 802 (1915)

[18] Davisson and Germer, Phys. Rev. **20**, 300 (1922)

[19] Stoekle. Phys. Rev. **8**, 534 (1916)

temperatures around $T=2000$, $b_0=48{,}200$, which is very close to the mean value obtained in the present investigation.

F. Deninger's[20] observations were not made under as good vacuum conditions as are available at present, and, therefore, correspond to values of b_0 which are much too high.

Quite recently Suhrmann[21] investigated the effect on the emission from tantalum of repeated treatments at high temperatures in vacuo. Owing to the form of cathode used by him, it is impossible to apply any cooling correction, but assuming even the whole cathode area to have been effective, the emission per unit area at any temperature is much higher than that obtained in the present investigation. The value of b_0 calculated from his data is about 42,000, and would certainly be less if a correction could be applied for the cooled area. In view of the observations made by the writers, it would seem necessary to conclude that the tantalum used by Suhrmann was not free from traces of active emittors.

RESEARCH LABORATORY,
GENERAL ELECTRIC COMPANY,
October 25, 1924.

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[20] F. Deninger, Ann. d. Physik **25,** 298 (1908)
[21] Suhrmann, Zeits. f. Physik **29,** (1923)