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ELECTRON EMISSION FROM THORIATED TUNGSTEN

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ABSTRACT

Constants of the electron emission from a monatomic layer of thorium on tungsten at temperatures from 1000° to 2000°K.—The electron emission for a monatomic layer of thorium on tungsten is best represented for zero field strength by the relation $I=3T^2\epsilon^{-30,500/T}$, where I is expressed in amps/cm². The emission was measured for different states of activation of the filament. If we let θ be the fraction of surface covered with thorium, then for $\theta<0.95$ (approximately) log A_θ varies linearly with b_θ where the emission for the given surface is represented by $I=A_\theta T^2\epsilon^{-b_\theta/T}$. It is also pointed out that the emission for a monatomic film of thorium on tungsten is greater than that observed for metallic thorium.

INTRODUCTORY REMARKS

AS SHOWN in a previous paper[1] the emission data for tungsten and tantalum are in satisfactory agreement with the equation

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

where A has the value 60.2 amp./cm² degree². The emission data for molybdenum were not in as good agreement, owing largely to the use of a temperature scale which more recent work has shown to be in error.[2]

Some observations by K. H. Kingdon[3] and further experiments by the writers led to the conclusion that in the case of the emission from monatomic layers, Eq. (1) no longer holds true, at least the constant A has a value different from 60.2. It therefore seemed important to obtain data as accurate as possible on the emission for one such case—that of thoriated tungsten.

As shown by I. Langmuir,[4] the emission from tungsten containing thoria is due to a monatomic layer of thorium on the surface, the thorium atoms being obtained by reduction at high temperatures of some of the thoria throughout the metal and the subsequent diffusion of the thorium atoms to the surface.

EXPERIMENTAL METHOD

In general, most of the emission data obtained by the writers and their associates have been secured with tubes similar to that described in the paper on the emission from tungsten, molybdenum and tantalum, that is the cathode was in the form of a V-shaped filament (total length 10 to 15 cm) and the anode consisted of a calcium deposit on the walls of the tube, as

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[1] S. Dushman, H. N. Rowe, Jessie Ewald and C. A. Kidner, Phys. Rev. **25**, 338 (1925).

[2] A recalculation of the electron emission data for this metal on the basis of Worthing's published data for the radiant emissivity (Phys. Rev. **28**, 190, 1926) leads to the values $A=60.2$, $b_0=51{,}300$, which are also in agreement with results obtained by C. Zwikker.

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

[4] I. Langmuir, Phys. Rev. **22**, 357 (1923).

shown in Fig. 1 of the above mentioned paper.[1] Some of the data mentioned in the latter part of this paper were taken with such tubes. For the purpose of reference, we will designate such tubes as type A.

However, the most accurate data were obtained on tubes (Type B) in which, instead of a V-shaped filament, a straight filament was used along the axis of the tube, with a molybdenum spring at one end to prevent bowing. Fine tungsten wires were welded onto the leads at each end of the filament and these were used to measure the voltage drop along the filament. The calcium deposit on the wall was obtained from two tungsten spirals (one at each end of the tube) containing calcium wire. A charcoal tube, which was immersed in liquid air during the measurements, was also sealed onto one end of the tube. Whether this extra precaution was really necessary is questionable, as more recent work, carried out since the observations recorded here were made, has shown that the residual oxygen pressure obtained with calcium or magnesium deposited on glass is *much lower* than that obtainable with charcoal in liquid air. However, it is certain that by adopting both these methods of cleaning up residual gases the vacuum attained was so good that the emission from an activated filament remained constant over a long period, and there was no difficulty in obtaining reproducible results.

TEMPERATURE SCALE

The temperature scale for tungsten used is that worked out by Dr. H. A Jones of this laboratory.[5]

The potential-difference (V) along the filament and the current (A) were measured on precision instruments. A first approximation to the correct temperature was obtained by calculating the value of the function A' ($=A/d^{3/2}$, where d is the diameter). The value of V was then corrected for end-loss effect in the manner indicated in a subsequent section and the corrected value of W' ($=W/ld$ where W is the corrected value of the power input and l is the length) calculated. The corresponding value of T was then obtained from a large scale plot of W' versus T.

Occasional checks on the temperatures calculated in this manner were obtained by direct pyrometry of vacuum lamps made up with the same wire as the filaments in the tubes used for electron emission measurements and aged in the same manner.

The diameter of the wire used was, of course, determined by weighing a long length of it and assuming the density to be 19.35.

LEAD-LOSS CORRECTION

As the filament is cooled near the leads, it is obvious that the potential difference along the filament, watts radiated, or electrons emitted, are less for a given current than they would be if the whole length of filament between leads were at the same temperature. The ratio between the value of the emission (or watts radiated, etc.) calculated for the latter case and that

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[5] H. A. Jones, Phys. Rev. **28**, 202 (1926). See also Forsythe and Worthing, Astrophys. J. **61**, 126 (1925).

actually observed is designated as the correction factor, f. It is evident that for a given length of filament, the lower the temperature, the greater the value of f; also that f must increase as the length of filament is decreased. In the case of emission data from thoriated tungsten, the range of temperatures used is much lower (1000–1600°K) than that for tungsten (1500–2300°K). Hence lead-loss corrections are much more important in this work than in the case of the other metals previously investigated.

The values of f were calculated by means of the relations derived by I. Langmuir.[6] Let H denote any function of the temperature, such as power radiated, luminosity, or electron emission, and let L denote *half the length* of filament between two leads. Also let ΔL_H denote the effective shortening due to cooling *at one lead*. Then:

$$f=\frac{L}{L-\Delta L_H}\doteq\frac{LdV/dL}{(L-\Delta L_H)dV/dL}=\frac{V+dV}{V+\Delta V-\Delta V_H} \tag{2}$$

where V is *one half* the total potential difference along the filament, ΔV is the correction for voltage drop (due to one lead), ΔV_H is the correction (in volts) for loss in value of H (due to one lead).

For lead-loss correction of potential drop in volts, the relation used was

$$\Delta V = .00013(T-400) \tag{3}$$

The value of ΔV_H is a complicated function of b_0 and the temperature. In the following table are given the values of ΔV_H used for the case of a surface completely covered with thorium.

T:	1000	1200	1400	1600
ΔV_H:	0.415	0.49	0.56	0.625

A method which suggested itself for eliminating the uncertainty in the value of the lead-loss correction consisted in *comparing measurements* on two different lengths of the same wire. This method was also used and the results obtained, as shown in a subsequent section, are in agreement with those obtained on the individual filaments after correcting for the effect of leads.

In the case of partly activated surfaces, b_0 is greater than for the fully activated condition and the value of ΔV_H is also different. In the present paper the values of this correction were obtained from the curves shown in Fig. 11 in the General Electric Review paper by the writers.[7]

CORRECTION FOR ANODE VOLTAGE

As pointed out in a previous paper by the writers,[1] the observed emission has to be corrected not only for cooling effect of leads, but also for the effect of anode voltage. Schottky has derived the following relation for calculating

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[6] I. Langmuir, Trans. Far. Soc. **17**, Part 3 (1921). See also S. Dushman and Jessie Ewald, Gen. Elec. Rev. **26**, 154 (1923). A more complete discussion of the method of deriving these formulas will appear in the near future in a paper by I. Langmuir and S. Dushman.

[7] It is to be noted that in this paper the values of ΔV_H are wrongly given as for *two* leads; whereas they should apply to only *one* lead.

the emission at zero field strength (i_0) in terms of the emission, i_V, at field strength dV/dx

$$\log_{10} i_V = \log_{10} i_0 + 4.39(dV/dx)^{1/2}/2.30T \qquad (4)$$

(It is assumed that the space currents are much below those corresponding to space charge,—a condition which was fulfilled in all cases.)

Schottky actually showed the validity of this relation for anode voltages up to 5000 for conditions in which the maximum value of dV/dx was considerably greater than those existing in the tubes used in the present investigations. More recent work by Mr. N. B. Reynolds in this laboratory has shown that Eq. (4) is also applicable to thoriated tungsten filaments for field strengths which are many times greater than those worked with in the present investigation.

According to this equation the values of i_0 for a given tube are obtained by plotting log i_V against $V^{1/2}$ at constant temperature. From the values of $\Delta \log i/\Delta V^{1/2}$ obtained for different temperatures an average value of $T\Delta \log i/\Delta V^{1/2}$ was derived and this was then used to calculate the value of i_0 at each temperature.

EMISSION DATA FOR FULLY ACTIVATED SURFACES

The most accurate data were obtained from measurements with two tubes, K-363 and K-364, which were made up with axially located filaments and special voltage leads, as described in a previous section. The tungsten wire used contained approximately 1.8 percent ThO_2, and had a diameter of 0.00876 cm.

Tube	Filament Length	Area
364	15.94 cm	0.438 cm^2
363	8.05	0.221
	$L_1 - L_2 = 7.89$	$S_1 - S_2 = 0.217$

While exhausting the tubes on the condensation pump, they were baked out for 2 hours at slightly above 360°C, in order to remove all gases from the

TABLE I

Data for determination of temperature scale.

Filament current (amp.)	P. D. along filament (volts) K363	K364	$\frac{V_1 - V_2}{7.89}$	Corrected P. D. along filament (volts) K363	K364	W'	T
0.25	0.792	1.73	0.119	0.96	1.90	3.40	1109
.30	1.085	2.34	.160	1.285	2.55	5.47	1209
.35	1.421	3.025	.203	1.635	3.24	8.10	1300
.40	1.796	3.769	.250	2.01	3.99	11.40	1385
.45	2.203	4.587	.302	2.43	4.82	15.50	1469
.50	2.642	5.454	.356	2.87	5.68	20.30	1545
.55	3.105	6.387	.416	3.35	6.63	26.10	1621
.60	3.610	7.372	.476	3.83	7.60	32.62	1695
.80	5.886	11.854	.757	6.10	12.09	69.20	1942
1.00	8.637	17.250	1.091	8.79	17.42	125.0	2220

TABLE II

Emission data for calculating the thermionic constants of thoriated tungsten filaments.

Emission data K-364					K-363	Difference in emission		
T	i_0	f	$\log_{10}I$ $+6$	f(obs)	i_0	Δi_0	$\log_{10}I+6$	$\log_{10}$ $(I/T^2)+12$
1109	1.17×10^{-6}	1.93	0.713	1.80	1.31×10^{-7}	1.04×10^{-6}	0.679	0.589
1151	3.18	1.77	1.109	1.63	6.24	2.56	1.072	.950
1209	1.40×10^{-5}	1.63	1.717	1.55	3.29×10^{-6}	1.07×10^{-5}	1.692	1.527
1244	3.17	1.56	2.052	1.50	8.34	2.34	2.033	1.843
1300	1.09×10^{-4}	1.48	2.565	1.52	2.67×10^{-5}	8.23	2.579	2.351
1336	1.94	1.44	2.805	1.36	6.27	1.31×10^{-4}	2.780	2.528
1385	5.38	1.39	3.232	1.42	1.59×10^{-4}	3.79	3.240	2.957
1421	9.46	1.36	3.467	1.36	3.08	6.38	3.468	3.163
1469	2.09×10^{-3}	1.32	3.800	1.32	7.23	1.37×10^{-3}	3.800	3.466
1500	3.32	1.30	3.993	1.24	1.29×10^{-3}	2.03	3.971	3.619
1545	7.14	1.28	4.319	1.29	2.54	4.60	4.326	3.948

glass walls and from the charcoal; the filaments were then flashed at about 2400°K for a couple of minutes and the calcium evaporated onto the walls. The exhaust was continued for a few minutes and the tubes sealed off.

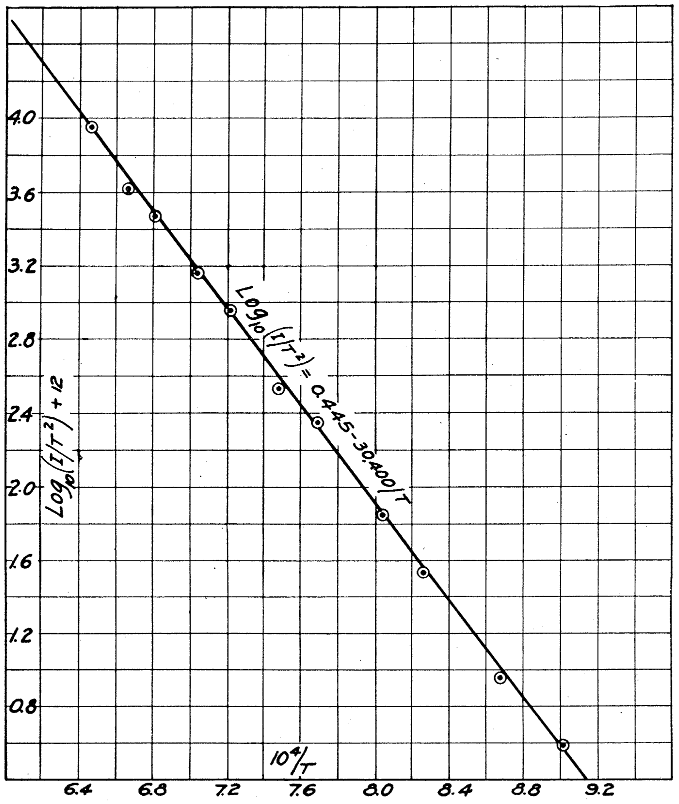

Fig. 1. Values of log (I/T^2) plotted against $10^4/T$. Tube K363.

Before taking data, the filaments were aged for 3 hours at 2400°K and then flashed for 1.5 minutes at 2900°K to reduce thoria. They were then activated at 2100°K or lower to a maximum emission, using 1500°K as testing temperature.

The data for the determination of temperature scale are given in Table I, while Table II gives the emission data used for calculating the thermionic constants. Under i_0 are given the emission data (after correcting for anode voltage), and in the case of K-364 there are also given the values of f used in calculating log I for each value of T. The differences between the values of i_0 at constant T for the two filaments are tabulated under Δi_0 and the last two columns give the corresponding values of log I and log (I/T^2).

From these values of log I and the values of i_0 observed for K-364 values of the correction factor for the latter filament were calculated. These are given under f (obs.).

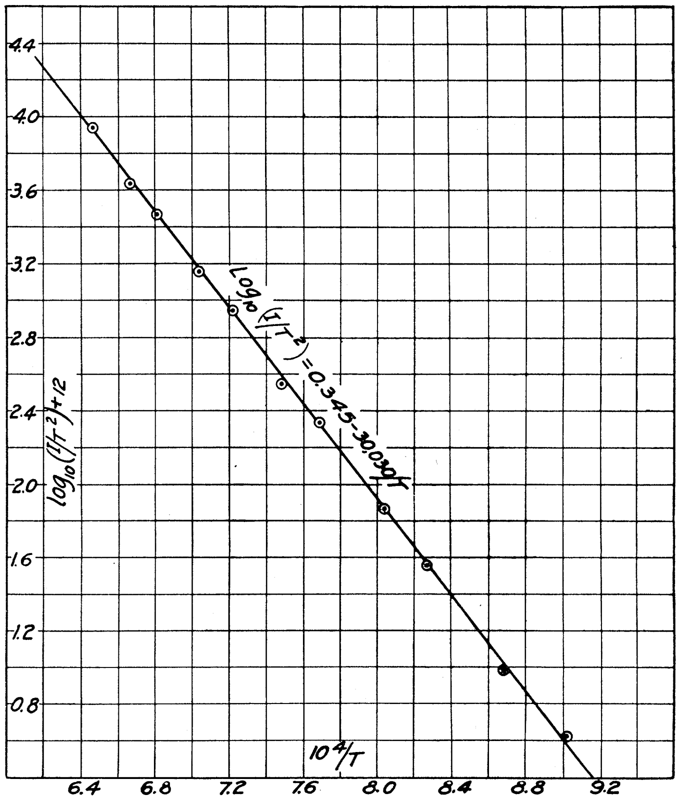

Fig. 2. Values of log (I/T^2) plotted against $10^4/T$. Tube K364.

Fig. 1 shows a plot of the values of log (I/T^2) given in the last column of Table II. Using the method of least squares these data give the values

$$A = 2.85 \text{ amps/(cm}^2\text{deg.}^2\text{)}; \; b_0 = 30{,}400 \text{ (deg. K)}.$$

Fig. 2 shows a similar plot of the data obtained for K-364. The resulting values are:

$$A=2.21,\quad b_0=30{,}030.$$

While the values of A and b_0 calculated for each set of data are slightly different, it is evident from the data given in Table II as well as the plots in the two figures, that the emission data are practically identical.

SOURCES OF ERROR

The possible sources of error involved in an accurate determination of the thermionic constants for an electron emitter such as a monatomic film of thorium on tungsten are even more numerous than those involved in measurements with pure metals. In the following section these are discussed briefly.

Incomplete activation. In order to obtain a completely covered film, special care must be taken to activate the filament for a long period at as low a temperature as possible. The exact procedure differs not only with the diameter of the filament, but also with the content of thoria and other factors which depend upon the previous metallurgical history of the wire. As will be shown in a subsequent section, a surface which is only 99 percent covered gives an emission which is approximately 90 percent of that of a fully covered film.

Positive ion bombardment. Even an extremely low pressure of residual gas (10^{-6} mm of Hg or less) will cause a considerable decrease in emission owing to bombardment by positive ions, and as shown by Kingdon, this effect increases rapidly with anode voltage. This was avoided in the present investigation by using calcium volatilized on the glass.

Temperature scale. This is undoubtedly the greatest source of error in all emission measurements. As it was impracticable to pyrometer the filaments *in situ*, the temperatures were calculated from the corrected power input or from the values of $V'A'^{1/3}$. However, for the same radiation intensity, different filaments may vary in temperature by as much as one percent from the average values given in the tables of characteristics, depending not only on the aging schedule, but also on the nature of the wire.

Now since

$$dI/I=(2+b_0/T)dT/T$$

it is evident that a one percent change in temperature at $T=1000$ causes a 30 percent change (approximately) in emission. Thus it is quite possible, especially at lower temperatures, to obtain a variation in emission at apparently the same temperature of as much as 30 percent.

End loss correction. The data for K-363 illustrate well the cooling effect of leads on short filaments. The values of f calculated for this case ranged from 1.75 at $T=1545$ to 2.12 at 1421 and to much greater values at lower temperatures. Consequently no accurate calculations could be made on the basis of the data for this tube alone. However, an inspection of Table II shows that when the data for K-364 and K-363 were combined, values of log I were obtained which were in good agreement with those obtained with K-364 alone, after introducing a correction for end loss. The agreement between values of f (obs), calculated in the manner discussed in a previous section, and values of f as actually used, is satisfactory, as it is within the limits of error of temperature determination.

Obviously the correction for end losses could be avoided by a construction of tube involving the guard ring principle. Data obtained on such a tube (No. 204) are given in Table III. The filament used had a diameter of 0.0103 cm and a total length of 19.65 cm. The length of the central portion on which emission data were taken was 10.3 cm. The anode consisted of three separated magnesium deposits on the glass wall.

TABLE III

Data obtained with tube in which end corrections were made unnecessary by the use of guard rings.

T	$\log(I/T^2)+12$	$10^3/T$	I	T (calc)
1155	.9368	0.8658	1.15×10^{-5}	1148
1216	1.4998	.8224	4.67	1208
1276	2.0150	.7836	1.69×10^{-4}	1266
1335	2.4579	.7491	5.12	1323
1385	2.8600	.7219	1.39×10^{-3}	1378
1453	3.3077	.6882	4.29	1447
1515	3.7100	.6601	1.18×10^{-2}	1511
1612	4.2738	.6204	4.88	1615

The fourth column gives the values of I (after correcting for Schottky effect) as calculated from the emission measurements on the central portion of the filament, while the second column gives corresponding values of log (I/T^2). The values of the thermionic constants obtained from the plot were $A=6.2$; $b_0=31{,}600$.

Comparing emission data as observed at corresponding temperatures, on this tube and on K-363, it is found that the latter are slightly higher. The last column of Table III gives values of T which would correspond to the observed values of I if we assume the thermionic constants $A=3$, $b_0=30{,}500$, which, as will be pointed out below, we believe to correspond to maximum emission data.

The difference between the values of T (calc) and values given in the first column is within the limits of experimental error, especially at the lower temperatures.

THERMIONIC CONSTANTS FOR FULLY ACTIVATED SURFACE

While observations have been made on a number of other tubes, the writers believe that the data obtained on K-364 and K-363 are the most accurate, since they correspond to maximum emission observed at any temperature. Taking into consideration the different possible sources of error, these results are best represented by the thermionic constants

$$A=3.0;\ b_0=30{,}500.$$

Table IV gives emission data calculated for the range $T=1000$ to $T=2000$°K. It is necessary to observe in this connection that owing to evaporation of thorium, the actually observed emission tends to be less than that given in the table at temperatures above 1800°K approximately. The third column in this table gives the efficiency of emission in amperes per watt—a property which is of extreme importance in the practical utilization of such filaments. The last column gives the value of the exponent n in the approximate equation

$$I = AT^n, \text{ where obviously } n = 2 + b_0/T.$$

TABLE IV

Emission data for a thoriated tungsten filament calculated for the range 1000° to 2000°K.

T (°K)	I (amp/cm²)	I/W (amp/watt)	n $d\ln I/d\ln T$
1000	1.73×10^{-7}	2.86×10^{-7}	32.5
1100	3.31×10^{-6}	3.21×10^{-6}	29.7
1200	3.95×10^{-5}	2.37×10^{-5}	27.4
1300	3.27×10^{-4}	1.27×10^{-4}	25.5
1400	2.03×10^{-3}	5.28×10^{-4}	23.8
1500	1.00×10^{-2}	1.811×10^{-3}	22.3
1600	4.06×10^{-2}	5.22×10^{-3}	21.1
1700	1.40×10^{-1}	1.29×10^{-2}	20.0
1800	0.428	3.03×10^{-2}	19.0
1900	1.164	6.28×10^{-2}	18.
2000	2.864	1.20×10^{-1}	17.3

The emission data actually obtained with different sizes of wire and in various types of tubes may vary from the values given in Table XI by as much as 25 percent, owing to experimental errors, such as those mentioned in previous paragraphs.

The following table (V) gives a comparison between emission data as observed on various tubes and values calculated from the observed power input in accordance with data given in Table IV. In all cases, corrections were made for lead losses and Schottky effect.

TABLE V

Comparison of emission data observed with values calculated from data of Table IV.

Tube No.	T	I (obs.)	I (calc.)
202	1450	3.2×10^{-3}	4.3×10^{-3}
	1650	5.25×10^{-2}	7.2×10^{-2}
161	1212	4.8×10^{-5}	5.0×10^{-5}
	1352	7.7×10^{-4}	8.5×10^{-4}
	1473	7.6×10^{-3}	6.5×10^{-3}
92B	1030	3.3×10^{-7}	4.5×10^{-7}
	1100	2.6×10^{-6}	3.3×10^{-6}
	1190	2.7×10^{-5}	3.0×10^{-5}
	1290	2.3×10^{-4}	2.6×10^{-4}
	1403	1.9×10^{-3}	2.0×10^{-3}
	1528	1.9×10^{-2}	1.6×10^{-2}

In each of these tubes the wire used was approximately 0.010 cm in diameter, but differed in thoria content and also in regard to other manufacturing details. The agreement between I (obs.) and I (calc.) is within the limits of experimental error in practically all the cases.

The following data (Table VI) were obtained with a thoriated wire 0.00403 cm diam. (1.59 mil) such as used in construction of commercial UX-201A tubes. The tubes used for this experiment were exhausted in the same manner as commercial 201A tubes. The filaments ($l=4.45$ cm) were mounted in the axis of a 0.5 inch diameter cylinder (about 1.5 inches long). The temperature was calculated from the observed power input (after correcting for lead-loss). The table gives the potential drop along the filament and the filament current, as well as the observed emission, while the last column gives the value of I (calc.) as taken from a curve plotted from the data in Table IV.

TABLE VI

Observed and calculated thermionic emission in a tube whose thoriated filament and manner of exhaustion were similar to those of the commercial 201A tubes.

Filament current (amp)	P. D. along filament (volts)	T	Emission at 100 volts (milliamp)		I (obs)	I (calc)
0.22	4.00	1825	24.0	1.40	0.595	0.550
.20	3.36	1740	9.7	1.47	.253	.220
.18	2.88	1650	3.05	1.54	.084	.076
.16	2.32	1550	0.82	1.69	.025	.021

The difference between I (obs.) and I (calc.) is easily accounted for by the effect of anode voltage. Recalculated for zero field strength the values of I (obs.) would have to be decreased about 10 to 15 percent.

As a matter of fact, numerous series of observations on commercial radiotrons containing thoriated filaments show uniformly good agreement with the values given in Table IV, after allowances are made for lead losses and probable error in temperature determination, provided, of course, that care has been taken to activate the filament completely.

VARIATION IN EMISSION WITH DEGREE OF ACTIVATION

Langmuir has defined θ, the fraction of the surface covered with thorium atoms, thus:

$$\theta_{\mathrm{I}}=(b_\theta-b_W)/(b_{Th}-b_W) \tag{5}$$

where b_θ, b_{Th} and b_W represent the work functions for the partly covered surface, completely covered surface, and pure tungsten respectively.

For approximate calculation of θ, Langmuir has also used the relation

$$\theta_{\mathrm{II}}=(\log I_\theta-\log I_W)/(\log I_{Th}-\log I_W) \tag{6}$$

where I_θ is the emission observed for the incompletely covered surface, I_W is the emission for pure tungsten, and I_{Th} is the emission for a surface completely covered with thorium.

Of these two methods for calculating θ, the first is the correct one from a theoretical point of view and should be used when values of the constant b_θ are available. On the other hand, Eq. (6) is very convenient to use in practice, and usually leads to values of θ which are not very different from those obtained by use of the more rigorous equation.

The condition which has to be fulfilled in order that $\theta_I = \theta_{II}$ is easily determined as follows: Assume $I_\theta = A_\theta T^2 \epsilon^{-b_\theta/T}$ with similar relations involving A_{Th} and A_W for the fully activated and pure tungsten surfaces respectively. Then

$$\theta_{\mathrm{I}} = \frac{\log(A_\theta/A_W) - \beta_\theta/T}{\log(A_{Th}/A_W) - \beta/T}$$

where $\beta = b_{Th} - b_W$ and $\beta_\theta = b_\theta - b_W$. But $\theta_{II} = \beta_\theta/\beta$; hence $\theta_I = \theta_{II}$ if

$$\frac{\beta_0}{\beta} = \frac{\log(A_\theta/A_W)}{\log(A_{Th}/A_W)}$$

i.e., if

$$\log A_\theta = \log A_W - \beta_\theta(\log A_W - \log A_{Th})/\beta \qquad (7)$$

That is, $\log A_\theta$ should be a *linear function* of β_θ. As will be shown, the experimental data do not lead to any such conclusion, and, therefore, the two definitions cannot be equivalent.

EMISSION DATA ON PARTLY ACTIVATED SURFACES

The most accurate series of data of this nature were taken with the tube K-364 described above. While emission data were also taken for different degrees of activation with tube K-363, they were not considered as very reliable. Firstly, for lower values of θ the emission at low temperatures decreased so much that with the instruments available no emission measurements could be obtained at temperatures below about 1300°–1400°K, while at higher temperatures (about 1650°K) the filaments begin to activate (that is, thorium diffusion begins to occur) at a rate, which, although very slow, is sufficiently great to interfere with accurate measurements. For pure tungsten itself, the lowest temperature at which emission data could be taken, with the instruments used, is about 1500°K. Therefore, it proved extremely difficult to obtain reliable emission data on deactivated surfaces for which θ approaches 0.20.

Table VII summarizes the results obtained with K-364 for different states of activation. The values of θ were calculated by means of Eq. (5) using the values $b_{Th} = 30{,}500$, $b_W = 52{,}400$.

TABLE VII

Results obtained with tube K-364 for different states of filament activation.

θ	A	b_θ	$\log_{10}A$
0.95	1.50	31,460	0.176
.83	2.08	34,150	.318
.72	3.74	36,570	.573
.56	7.76	40,070	.890
.43	10.86	42,840	1.037
.25	15.81	47,050	1.199
.18	(8.2)	48,360	.914

Plotting log A_θ against b_θ (see Fig. 3) it is observed that above a minimum value (corresponding to $b_\theta = 31{,}500$) four out of six points lie on a straight line passing through the value of log $A = 1.78$ which corresponds to pure tungsten. The values of A for $\theta = 0.25$ and $\theta = 0.18$ were obtained from data which were not nearly as reliable as those obtained for larger values of θ.

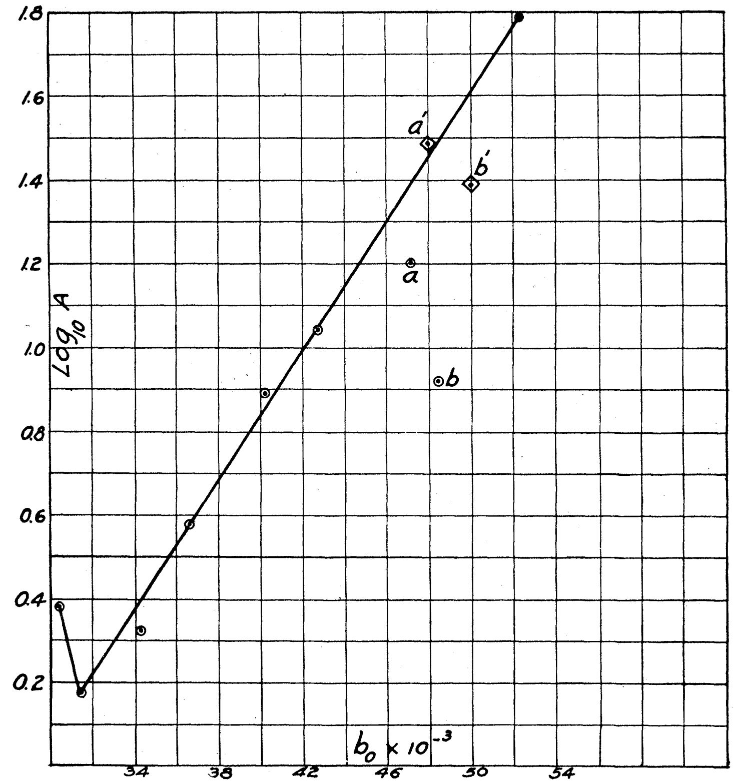

Fig. 3. Plot of log A_θ against b_θ.

In a discussion of these results with Dr. Kingdon, he suggested that a formula of the form

$$A_\theta = A_W(1-\theta)^n + A_{Th}\theta^n$$

might fit the observed data, since such an expression passes through a minimum value as θ is decreased. Empirically, it was found that $n = 2.5$ gives a better agreement with the observations than larger or smaller values of n, but it is even less satisfactory than the linear relation between log A_θ and b_θ suggested above.

One fact that must be considered is this, that a relatively small change in b_θ affects the value of A_θ a great deal. Thus, in the case of $b_\theta = 47{,}050$, if this value is decreased to $b_\theta = 48{,}000$, the resulting value of A_θ for constant emission at $T = 1500$, is found to be 29.8, which brings this point almost on the straight line.

Similarly for constant emission at $T=1500$, the values $A_\theta=24.6$ and $b_\theta=50{,}000$ correspond to $A_\theta=8.2$ and $b_\theta=48{,}360$. It should be stated that the emission data on which the latter values were based were taken over the range $T=1421$ to $T=1575$, which was undoubtedly too low a range for any great degree of accuracy.

From these considerations it would appear that the actual observations are not in disagreement with the tentative conclusion that from $\theta=0.95$ to $\theta=0$, log A varies linearly with b_θ (and therefore with θ).

Observations on other tubes, although not so accurate, were found to be in qualitative agreement with the observations discussed above in the conclusion that A_θ passes through a minimum value for a value of θ close to unity, as b_θ is increased.

Discussion of Results

In the earlier paper published by the writers,[1] the work function b_0 for a completely activated surface was given as 34,100. This was calculated on the assumption that $A=60.2$. However, it was observed that the actual slope of log (I/T^2) against $1/T$ gave consistently lower values of b and it was assumed that this was probably due to errors in temperature scale. Since then, Dr. Jones has completed his work on this problem and on the basis of his results the earlier emission data are found to be in very good agreement with the data given in this paper.

K. H. Kingdon[3] has also published emission data for thoriated tungsten, for both the completely activated and incompletely activated surfaces. Using the guard ring principle he obtains for $\theta=1$, the values $A=7$, $b_0=31{,}200$ (at anode potential of 150 volts), and for partly activated surfaces, the relation

$$A_\theta=(7^\theta+60^{1-\theta}-1)\ \text{amps/(cm}^2\text{deg.}^2)$$

Values of θ were calculated from observed values of b_θ by means of Eq. (5).

The filament temperatures were determined from the heating current and Dr. Kingdon believes that the accuracy of his temperature determination was therefore not as great as that obtained in the present investigation. At $T=1000$, the emission calculated on the basis of Kingdon's constants is practically identical with that given in Table IV, while at $T=1500$, Kingdon's constants lead to a value 50 percent greater, which is probably to be accounted for by two sources of error: (1) failure to correct for effect of anode voltage, and (2) difference of about 1 percent in temperature at the upper point of his working range.

Kingdon's observations on the variation of A_θ with b_θ are in qualitative agreement with those obtained in the present work, but there is a lack of quantitative agreement.

Interpretation of Observed Value of A for Completely Covered Film of Thorium on Tungsten

Careful measurements on tungsten, molybdenum and tantalum in this laboratory, as well as similar measurements by Germer and Davisson on tungsten and by C. Zwikker[8] on tungsten and thorium lead to the conclusion that for at least these four metals the constant A has the value 60.2 (within the probable limits of error in determination of temperatures).

The writers believe that this conclusion is probably valid for all pure metals (subject to slight differences due to effect of surface charge, as pointed out by Bridgman[9]). On the other hand, the present observations for the case of monatomic layers of thorium on tungsten, Kingdon's measurements for caesium on tungsten, and the results obtained for Wehnelt cathodes show that for these surfaces A is less than 60.2.

It is of interest in this connection to point out that while A is less than 60.2 for a monatomic layer of thorium on tungsten, the value of b for the monatomic layer is less than that for metallic thorium, as is evidenced by the published data of Zwikker and is also confirmed by recent measurements in this laboratory on some thorium wire kindly provided by Dr. Myers of the Research Laboratory of the Westinghouse Company.

Also some recent measurements in this laboratory on monatomic layers of zirconium on tungsten[10] show that in this case $A=5$ and $b_0=36{,}500$, while for metallic zirconium Zwikker gives the values $A=3000$, $b_0=52{,}200$. Thus the emission over the range of working temperatures is lower for metallic zirconium than for the film.

There is, therefore, every reason for believing that for all cases where we have a monatomic layer of a more electropositive metal on another metal, the value of A is less than 60.2. On the other hand, for surfaces more or less partly covered with oxygen, A is greater than this value, and the same conclusion apparently holds true in all cases where we have a monatomic layer of a more electronegative element, as, for instance, phosphorus or iodine on tungsten.[11]

The significance of these deviations in the value of A from the so-called constant value is probably to be found in a consideration of Bridgman's theory of the effect of surface charges and of the validity of the third law for monatomic films. The discussion of this subject must, however, be deferred for further consideration in a paper by Dr. L. Tonks and the first named writer, which will appear in the near future.

Research Laboratory,
General Electric Company,
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[8] C. Zwikker, Proc. Royal Academ. Amsterdam **29**, 792 (1926).

[9] P. Bridgman, Phys. Rev. **14**, 306 (1909).

[10] To be published in the near future.

[11] As shown by observations made by the writers.