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WORK FUNCTION, IONIZATION POTENTIAL, AND
EMISSIVITY OF URANIUM

by

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I. INTRODUCTION

In previous investigations^(1,2) it was shown that measurements of certain properties of uranium metal are affected by gas pressures as low as 10^{-7} mm Hg and that better vacuum conditions would be necessary if certain types of measurements are to be reliable. The purpose of this investigation was four-fold: 1) to establish the technique of maintaining ultra-high vacuum conditions at high temperatures, 2) to measure the work function of uranium metal, 3) to investigate the surface ionization of uranium atoms on tungsten, and 4) to measure the emissivity of uranium via the reflectivity.

Three independent measurements of the work function of uranium have been reported: 4.32 ev by the contact potential method,⁽³⁾ 3.63 ev by the photoelectric threshold method,⁽⁴⁾ and 3.27 ev by thermionic emission.⁽⁵⁾ Preliminary measurements in this Laboratory⁽²⁾ indicated a value below 4 ev and suggested that Rentschler, Henry and Smith's value of 3.63 ev is probably the most reliable.

Kiess, Humphreys and Laun⁽⁶⁾ estimated an approximate value of 4 ev for the ionization potential of uranium from the fact that they found no spectral lines of neutral atoms below 2900 Å.

Hole and Wright⁽⁵⁾ found an average value of 0.5 for the emissivity of uranium at 6700 Å, and Wahlin⁽⁷⁾ calculated an emissivity of 0.45.

II. EXPERIMENTAL MEASUREMENTS

A. Methods

1. Vacuum. The method of attaining ultra-high vacua was based on the techniques of Alpert.⁽⁸⁾ In this method the system is thoroughly degassed, sealed off from the diffusion pumps, and evacuated by the pumping action of an ionization gauge without the use of refrigerants.

2. Work Function. Measurements of the work function were made on deposits of uranium evaporated on tungsten. The electron emission from deposits of varying thicknesses was measured as a function of the temperature, at temperatures at which the uranium-tungsten films were stable, according to the Richardson equation^(9,10)

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$$I = AT^2 \exp\left(\frac{-\phi e}{kT}\right), \quad (1)$$

where I is the electron emission in amp cm⁻², $A = 4\pi mk^2 eh^{-3} = 120$ amp cm⁻² deg⁻², ϕ is the work function, and $e/k = 11606$ deg ev⁻¹.

3. Surface Ionization. The ionization of uranium was investigated by means of the positive ion current from a tungsten surface at elevated temperatures under bombardment by neutral uranium atoms. The theory of surface ionization has been discussed by Langmuir,⁽¹¹⁾ Becker,^(12,13) Fowler⁽¹⁴⁾ and others, and the statistical relationships are given by the Langmuir-Saha equation

$$\frac{n_+}{n_a} = \frac{Q_+}{Q_a} \exp\left[\frac{(\phi - I^*) e}{kT}\right], \quad (2)$$

where n_+/n_a is the ratio of ions to atoms leaving the surface, Q_+ and Q_a are the electronic partition functions of the ion and atom, respectively, at temperature T , ϕ is the work function of the surface, and I^* is the ionization potential of the atom. The partition function of the atom, Q_a , can be calculated from the data of Kiess, Humphreys, and Laun,⁽⁶⁾ but the spectral data for the uranium ion have not been resolved.^(15,16) However, Q_+/Q_a is probably near unity. Equation (2) holds only at temperatures at which the surface is essentially clean and the work function is not lowered by the absorption of electropositive atoms, and under zero space charge conditions.

4. Emissivity. The emissivity of uranium was calculated from the reflectivity of a thick film deposited in vacuo on an optically flat glass surface.

B. Apparatus

The apparatus is shown in Figure 1. The tantalum evaporator, 1.5 cm long and 1.0 cm in diameter with 0.15-cm walls and with a 1-mm depression in the top, was mounted on 0.060-in. diameter tungsten rods which were thinned to about 0.030 in. along the top 2 cm to minimize conduction losses. A hairpin tungsten filament, 0.006 in. in diameter and 3 cm long, was mounted inside the cylinder on a second pair of 0.060-in. diameter tungsten rods. The tungsten leads were sealed directly into Pyrex and the ends of the leads were sealed with a gold-nickel alloy to prevent leakage through the core of the tungsten.

The grid was constructed of 0.003-in. diameter tantalum wires with 1-mm spacing. The over-all dimension of the grid was 1.5 x 1.0 cm and was mounted 0.5 cm above the top of the evaporator, as shown.

The tungsten ribbon, 0.060 in. x 0.002 in., was shaped as shown to expose a length of 0.5 cm to grid and evaporator and was mounted 0.5 cm

Figure 1. Apparatus

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from the grid on a pair of 0.060-in. diameter tungsten leads. A shadow shield was sealed to the leads to prevent electrical leakage through the uranium film that later formed over the inner surface of the bulb.

The inner surface of the optical window, which was provided to calibrate the temperature of the ribbon and for the formation of a uranium mirror, was protected by a thin nickel disc held in place by a small magnet.

The WL-5966 ionization gauge used was the Bayert-Alpert inverted type of ionization gauge⁽⁸⁾ capable of measuring pressures as low as 10^{-12} mm Hg. The diaphragm valve, a slight modification of that described by Alpert,⁽⁸⁾ was operated by a differential screw. The exhaust side of the valve was connected to the usual type of vacuum system incorporating a liquid nitrogen trap, mercury vapor diffusion pump, mechanical pump and VG1A ionization gauge. The pumping speed of this system was estimated to be 2 liter sec^{-1} at the valve. An electrically heated oven enclosing all parts shown in Figure 1 was provided for degassing.

The electrical circuits are shown in Figure 2. The tungsten ribbon was heated resistively by direct current from a six-volt storage battery. Series resistors R_1 , 0 to 0.015 ohm in 0.0015-ohm steps and R_2 , 0 to 0.15 ohm in 0.015-ohm steps, were constructed from four-pole decade switches carrying parallel manganin wire resistances. R_3 was a series of manganin plug-in type resistances. The heating current was measured to within 0.02% by a potentiometer across a standard 0.01-ohm shunt. Grid potentials were supplied by a 3000-volt power supply, either pole of which could be grounded. The evaporator was heated by electron bombardment from a 0-3000 volt, 0-250 ma power supply. The bombarding power was stabilized by an emission regulator in series with the filament supply and measured with a calibrated voltmeter and milliammeter.

The electronic circuit for the operation of the WL-5966 ionization gauge was built around a power supply furnishing degassing power and electrometer voltages and an electrometer, designed and built by the ANL Electronics Division, employing a CK-5886 electrometer tube and two 12AY7's and one 12AU7 in a three stage 100% feed-back amplifier. Full scale pressure ranges from 10^{-3} to 10^{-10} mm Hg were provided.

C. Procedure

1. Testing of Vacuum System at High Temperatures. It was necessary to apply a rigorous bake out and degassing procedure to the system to achieve the vacua desired. At 10^{-6} mm Hg or lower, a bake out at 400°C for 4 hours was followed by degassing of the metal parts for three hours: the ribbon at 2600°K by resistive heating, the evaporator at 2000°K

Figure 2.

Electrical Circuit.

by electron bombardment, and the grid at 2000°K by electron bombardment making use of the electron emission from the ribbon. The elements of the ionization gauge were degassed simultaneously by glowing both filaments and bombarding the grid and collector. This cycle was repeated several times after which the valve was closed, and the limiting pressure of 2×10^{-10} mm Hg was reached by the pumping action of the ionization gauge. Overnight, without ionic pumping, the pressure was found to rise to about 10^{-8} mm Hg corresponding to a rate of rise of pressure of 2×10^{-11} mm Hg per minute, which is fully explained by the diffusion of atmospheric helium through the glass.⁽¹⁷⁾ After this treatment it was possible to raise the ribbon temperature to 2400°K and the evaporator to 2000°K and maintain the pressure below 5×10^{-10} mm Hg.

The temperature of the ribbon was determined as a function of the heating current by an optical pyrometer which had been calibrated at the copper point and the calibration extended to 2600°C by means of rotating sectors.⁽¹⁸⁾ Each reading on the ribbon was corrected for the transmissivity of the window and the brightness temperature of tungsten.⁽¹⁹⁾

The temperature calibration was checked by a determination of the Richardson constants of tungsten according to Eq. (1). The data are given in Table I and the plot of $\log i/T^2$ against $1/T$ is shown in Figure 3.

Table I
EMISSION DATA FOR CLEAN TUNGSTEN

i (amp)	T (°K)	$10^4/T$	$\log i/T^2$
3.00×10^{-8}	1533	6.523	-13.895
6.11×10^{-7}	1673	5.977	-12.661
1.06×10^{-5}	1827	5.473	-11.499
1.31×10^{-4}	1989	5.028	-10.479
1.81×10^{-3}	2190	4.566	-9.424
$2.78 \times 10^{-2^a}$	2485 ^a	4.024	-8.345
$9.73 \times 10^{-5^a}$	2358 ^a	4.240	-8.757
4.45×10^{-4}	2077	4.815	-9.976
4.39×10^{-5}	1912	5.230	-10.920
2.29×10^{-6}	1739	5.750	-12.122
1.48×10^{-7}	1605	6.230	-13.240
$\log i/T^2 = \frac{-22939 \pm 39}{T} + (1.0605 \pm 0.0219)$			
$\phi = 4.55 \pm 0.01$		$A = 115 \pm 6^b$	

^aNot included in least squares equation. Under the experimental conditions used saturation current was not drawn above 2200°K.

^bEmitting area = 0.1 cm²

Figure 3.

Richardson Plot for Clean Tungsten.

of the evaporator through the side arm under a constant flow of purified helium. Bake out was followed by degassing of the grid, ribbon and ion gauge and a slow increase of evaporator temperature to 2000°K. The evaporator was held at 2000°K until a noticeable deposit of uranium appeared on the walls. The valve was closed and further pumping was effected by the ionization gauge and the gettering action of the uranium deposit.

The tungsten ribbon was cleaned at 2400°K and a measure was taken of the pressure of thermionically important gases by measuring the change of emission with time at constant temperature. For this measurement the potentials of the grid and evaporator were set at 400 v. Langmuir(21) reports the number of tungsten atoms per square centimeter of well-aged tungsten(20) to be 1.92×10^{15} and gives as the accommodation coefficient of oxygen on tungsten a value of 6×10^{-3} at 1500°K.(22) Bosworth(23) reports a contact potential of oxygen against tungsten as varying very close to linearity from zero at zero concentration to 1.8 ev at one monolayer. With this data, Eq. (1) and the relationship,

$$n = \frac{pN_0}{\sqrt{2\pi MRT}} \text{ atoms cm}^{-2} \text{ sec}^{-1} \quad (3)$$

from the kinetic theory, the following expression for the pressure in terms of the fractional rate of change of electron emission at 1500°K can be derived:

Values of $\phi = 4.55$ and $Aa = 11.5$ were found. During the degassing procedure the ribbon had been subjected to a treatment by which the ribbon had become well-aged according to Taylor and Langmuir(20) and the emitting area could be taken as 1.35 times the geometric area(21) or 0.1 cm^2 . The Richardson constant $\underline{A}$ was found to be 115.

At this point it was established that by the use of Alpert's techniques ultra high vacua can be maintained at high temperatures. About 500 mg of anodically cleaned uranium metal, containing less than 100 ppm of impurities, were placed on the top

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$$p_{\text{mm Hg}} = -6.4 \times 10^{-5} \frac{di}{idt} \quad (4)$$

This represents the fractional change of emission as electronegative (oxygen) atoms at pressure p mm Hg are deposited on tungsten at 1500°K . At several different times the emission at 1500°K was observed to remain constant to within 1% over the period of a day, from which a maximum pressure of 3×10^{-11} mm Hg of thermionically important gases is calculated from Eq. (4). Later it was found that the emission from a deposit of several monolayers of uranium on the tungsten ribbon (see next section) at a given temperature around 1300°K could be reproduced to within 1% after the deposit had remained at room temperature over a week-end. On the assumption that every atom striking this highly active surface reacted with the surface, the pressure of thermionically important gases could not have been above 10^{-13} mm Hg.

2. Electron Emission and Work Function. To determine the characteristics of the uranium deposits on tungsten qualitatively, the rate of change of electron emission at a constant arrival rate of uranium atoms at the surface was measured. For these measurements the galvanometer was placed at -135 v, the grid at +100 v, the evaporator at +1000 v, and the filament emission was adjusted to about 80 ma. The results are shown in Figure 4, in which the emission is plotted against time of deposition. Below 1800°K the emission rose to a maximum at 4 minutes, then fell to a lower value. This is characteristic of the emission from a surface on which the concentration of adsorbed electropositive atoms is increased to and beyond one atomic layer.⁽²⁴⁾ Below 1800°K the rate of evaporation is less than the deposition rate and multiple layers are built up. Each curve at temperatures above 1800°K represents the formation of an equilibrium concentration of less than one atomic layer dependent upon deposition rate and surface temperature. The equilibrium current increases with increasing ribbon temperature up to about 2000°K , then decreases to 2200°K , and represents the competition between increasing temperature and increasing work function (decreasing surface concentration) according to Eq. (1). Above 2200°K the emission from the clean tungsten becomes large compared with the emission from the small fraction of the surface covered with uranium atoms.

Since it was not possible to measure the evaporator temperatures pyrometrically because of the formation of deposits on the window, the times of maximum emission taken from curves such as shown in Figure 4 at surface temperatures in the range $1200 - 1300^\circ\text{K}$ were used to determine arrival rates for given power inputs. Arrival rates were calculated assuming 1) the area of the ribbon to be 0.1 cm^2 , 2) a complete atomic layer of uranium to contain one atom of uranium for two atoms of tungsten, 3) maximum emission to occur at one complete atomic layer, and 4) the rate of evaporation of uranium from an adsorbed atomic layer

Figure 4.

Change of Electron Emission at Constant Rate of Deposition of Uranium on Tungsten.

to be negligible compared with the arrival rate. The first assumption is based on the geometric area and the roughness factor of well-aged tungsten.(20) The second is based on the size of the uranium atom and the arrangement of tungsten atoms in the (110) planes which are developed upon aging. The third is based on the behavior of cesium, barium, and other electropositive atoms adsorbed on tungsten. The fourth assumption is made even though a rate of evaporation of uranium at 1300°K of 2.7×10^{10} atoms $\text{cm}^{-2} \text{sec}^{-1}$ is calculated from Eq. (3) and the data of Rauh and Thorn.(1) The true rate of evaporation from a single adsorbed atomic layer is probably many times less because of the powerful forces exerted on the adatoms by the underlying tungsten atoms.(21) Arrival rates of 2.7, 4.9, 7.5, and 13.7×10^{12} atoms $\text{cm}^{-2} \text{sec}^{-1}$ for power inputs of 80, 85, 90, and 100 watts, respectively, were determined experimentally in this manner. The evaporator temperatures were determined from these arrival rates, Eq. (3), and the cosine law. The arrival rate $\underline{Z}$ atoms $\text{cm}^{-2} \text{sec}^{-1}$, is given by

$$Z = \frac{pN_0}{\pi \sqrt{2\pi MRT}} \iint \frac{\cos^2 \theta}{\ell^2} ds_1 ds_2 \quad (5)$$

for the case ds_1 parallel to ds_2 . From Figure 5, Eq. (5) becomes

$$Z = \frac{pN_0}{\pi \sqrt{2\pi MRT}} \int_{-Y}^{+Y} \int_0^{2\pi} \int_0^R \frac{d^2 w}{(d^2 + y^2 + r^2 - 2yr \cos \alpha)^2} r dr d\alpha dy \quad (6)$$

Integration over the limits yields

$$Z = \frac{pN_0 w}{\sqrt{2\pi MRT}} \left[\frac{2R^2 Y}{R^2 + d^2} - \frac{4R^2 d^2 Y^3}{3(R^2 + d^2)^3} \right] = \frac{0.195 pN_0}{\sqrt{2\pi MRT}} \quad (7)$$

Figure 5.

Geometry Factor.

arrival rates the surface of the tungsten remained clean above 2400°K and multiple layers were formed below 1800°K.

Work function determinations were made in the following manner. Uranium was evaporated on the tungsten for a given time at a known deposition rate. Under an accelerating potential of 400 volts, electron emission from the surface was measured as a function of the surface

From Eq. (7) and the data of Rauh and Thorn,⁽¹⁾ evaporator temperatures of 1535, 1560, 1580, 1615°K for input powers of 80, 85, 90 and 100 watts, respectively, were calculated. If an average emissivity of 0.4 be assumed for the evaporator surface, temperatures of 1530, 1560, 1580, and 1620°K for input powers of 80, 85, 90, and 100 watts are calculated from the Stefan-Boltzmann law, indicating an over-all consistency in these calculations.

Measurements of the type shown in Figure 4 were carried out at several arrival rates and at surface temperatures in the range 2200 to 2500°K. For all

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temperature in the range 1200-1550°K. Richardson measurements of this type were made on twenty deposits ranging in thickness from 1 to 200 atomic layers. The data, given in Table II, were plotted as $\log 1/T^2$ against $1/T$ in accordance with Eq. (1), from which ϕ and $\underline{A}$ and their probable errors were calculated from the slope and intercept by the method of least squares. A few of the plots are given in Figure 6. In Figure 7 the measured values of ϕ and $\underline{A}$ are plotted against the thickness of the deposit. At 15 atomic layers ϕ was found to reach a limiting value of 3.47 ± 0.03 ev and $\underline{A}$ a limiting value of 114 ± 12 amp cm^{-2} deg^{-2} . The independence of ϕ and $\underline{A}$ on the depth of the deposit beyond 15 atomic layers and the nearly theoretical value of $\underline{A}$ support this value of the work function of uranium, which is in fair agreement with the value of Rentschler, Henry, and Smith.(4)

This value of the work function is also supported by a treatment of the data that does not involve a knowledge of the amount of uranium deposited on the tungsten for any given measurement. In Figure 8 $\log \underline{A}$ is plotted against the corresponding value of ϕ . Least squares analysis rejected points 1, 2, and 10 (Table I) successively by the criterion that the residuals in $\log \underline{A}$ were greater than five times the probable error at the corresponding value of ϕ . The least squares line shown in Figure 8 is given by

$$\log A = (2.450 \pm 0.066)\phi - (6.470 \pm 0.221) \quad .$$

From this equation at $A = 120$, $\phi = 3.49$, which agrees within the probable error with the value given above. Further, at $\phi = 3.47$, $A = 117$, which agrees within the probable error with the value of $\underline{A}$ given above.

It was found that the temperature of the ribbon in the range 1250-1500°K was not changed appreciably by a deposit of uranium on the surface. The resistance of the ribbon could not have been decreased by the deposit itself, but any large change in resistance would have been caused by a change in temperature which at constant heating current might have been caused by a difference in emissivity of the surface. By the use of a second potentiometer across the leads the resistance of the ribbon was measured as a function of the heating current for the ribbon clean and with a deposit of 40 atomic layers. Least squares analysis was applied to both sets of measurements; the slopes and intercepts were found to agree within their probable errors, but resistances calculated at the ends of the temperature range differed by about 0.2% which was outside the probable error. However, this difference was equivalent to at most a change of 3 degrees.(25)

3. Ion Current Measurements. The apparatus was not properly designed for quantitative positive ion measurements. The bombarding filament was not adequately shielded and unless the ribbon potential were a few volts positive with respect to the filament, no grid potential could shield the ribbon from stray electrons from the filament. This placed the evaporator at +600 to +1500 volts and required a grid potential of -2000 to -3000 volts

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Table II
WORK FUNCTION EMISSION DATA

Observation	Depth of Deposit, Atomic Layers	$10^4/T$	$\log 1/T^2$	ϕ	A	Observation	Depth of Deposit, Atomic Layers	$10^4/T$	$\log 1/T^2$	ϕ	A
1	1	7.315 7.960 8.305 7.630 7.065 5.400	-11.402 -12.350 -12.393 -11.955 -11.938 -10.609	3.00 ± 0.02	4.3 ± 0.8 0.6	9c	15c	7.130 7.690 7.940 7.440 7.320	-11.399 -12.336 -12.768 -12.905 -11.710	3.37 ± 0.01	53.7 ± 4.3 - 3.0
2	3.1	6.660 7.305 7.900 5.229 7.435 5.950	-10.342 -11.316 -12.259 -12.159 -11.532 -10.790	3.07 ± 0.02	9.5 ± 1.1 - 1.9	9d	20d	7.130 7.690 7.940 7.750 7.360 7.115 7.480 7.845	-11.414 -12.294 -12.646 -12.444 -11.800 -11.391 -12.024 -12.664	3.47 ± 0.02	97.2 ± 16.3 - 14.0
3	4.2	6.660 7.310 7.920 8.225 7.555 5.945 7.370	-10.280 -11.285 -12.274 -12.746 -11.658 -10.712 -12.192	3.14 ± 0.02	18.9 ± 2.5 - 2.3	10	2.5	7.430 7.710 3.040 7.905 7.309 7.080	-11.711 -12.152 -12.662 -12.445 -11.496 -11.152	3.11 ± 0.01	9.4 ± 0.9 - 0.3
4	4.0	6.445 7.080 7.720 3.153	-10.104 -11.050 -12.074 -12.760	3.20 ± 0.02	25.0 ± 3.0 - 2.7	11	4	7.540 7.920 7.980 7.290 7.989	-12.003 -12.620 -12.236 -11.582 -11.235	3.28 ± 0.01	29.8 ± 3.5 - 3.2
5	5	6.575 7.150 7.750 8.100	-10.313 -11.093 -12.033 -12.587	3.16 ± 0.02	20.2 ± 2.6 - 2.5	12	10	7.390 7.570 7.960 7.750 7.309 7.765	-11.842 -12.133 -12.794 -12.433 -11.660 -11.269	3.38 ± 0.03	60.4 ± 16.1 - 12.3
6	3.5	7.250 7.500 7.750 3.235 7.165 7.000	-11.338 -11.874 -12.144 -12.962 -11.182 -10.909	3.21 ± 0.02	26.8 ± 5.2 - 4.4	13	15	7.130 7.430 7.745 7.590 7.210	-11.416 -12.788 -12.470 -12.023 -11.528	3.44 ± 0.02	191.3 ± 22.9 - 18.5
7a	9.5	7.139 7.665 7.985 7.360 7.090 6.825 6.657	-11.342 -12.249 -12.799 -11.722 -11.280 -10.773 -10.527	3.42 ± 0.02	95.7 ± 16.3 - 13.9	14	20	7.130 7.930 7.590 7.395 7.150 7.499 7.730 7.510 7.059	-11.414 -12.810 -12.184 -11.694 -11.446 -11.696 -12.553 -12.906 -11.276	3.48 ± 0.02	126.3 ± 25.4 - 21.5
7b	13a	7.250 7.740 7.490 7.130 7.665 6.579 7.180 7.710	-11.632 -12.335 -12.936 -11.423 -12.351 -10.695 -11.510 -12.440	3.47 ± 0.01	119.7 ± 2.6 - 3.3	15	30	7.490 7.265 7.130 7.460 7.630 7.770	-12.030 -11.609 -11.438 -12.002 -12.304 -12.554	3.49 ± 0.03	101.0 ± 24.3 - 19.7
8	2.	7.130 7.750 7.635 7.470 7.330 7.170 7.090 7.960	-11.454 -12.874 -12.404 -12.034 -11.784 -11.524 -11.313 -12.892	3.45 ± 0.01	92.5 ± 2.5 - 3.3	16	45	7.335 7.535 7.150 7.360 7.470 7.740 7.270	-12.689 -12.165 -11.495 -11.850 -12.147 -12.514 -11.690	3.48 ± 0.02	113.7 ± 21.5 - 18.2
9a	5	7.139 7.755 8.125 7.835 7.420	-11.245 -12.253 -12.845 -12.383 -11.685	3.21 ± 0.02	20.7 ± 4.9 - 3.9	17	200	7.525 7.500 7.610 7.120 7.250 7.236 7.315 7.335 7.519 7.625 7.470	-12.186 -12.310 -12.350 -11.479 -11.724 -11.754 -11.832 -11.861 -12.103 -12.382 -12.196	3.50 ± 0.02	126.4 ± 27.0 - 22.2
9b	13b	7.130 7.630 7.940 7.490 7.310 7.065	-11.357 -12.393 -12.746 -11.913 -11.575 -11.265	3.37 ± 0.01	54.3 ± 2.3 - 2.7						

- (a) 9.5 atomic layers deposited on deposit of 7a.
 (b) Five additional layers deposited on deposit of 9a.
 (c) Five additional layers deposited on deposit of 9b.
 (d) Five additional layers deposited on deposit of 9c.

Figure 6.

Richardson Plots of Emission from Uranium Surfaces.

Figure 7.

ϕ and A as Function of the Number of Depth of Deposit.

in order to suppress electron emission from the ribbon at 2400°K. Under the conditions +1000 volts on the evaporator, - 2000 volts on the grid, filament cold, tungsten surface at 2400°K, all currents registering on the galvanometer were reduced below 10^{-9} amp. Measurements were made under these conditions by fixing the arrival rate and measuring the positive ion current from the hot tungsten surface as uranium atoms reached the surface at some constant rate. Figure 9 shows the observed positive ion currents, corrected for photoelectrons from the grid, measured at four arrival rates as a function of the temperature of the tungsten surface. In all cases these currents exceeded the arrival rate above 2400°K. The measured currents were probably the sum of positive ions from the ribbon and secondary electrons released from the grid by the high energy ions. The secondary electron possibility is borne out in Figures 10 and 11. In Figure 10 the

Figure 8.

Log A vs Corresponding
Value of ϕ .

Figure 9.
Apparent Ion Currents
as Functions of Surface
Temperature at Constant
Arrival Rates of Atoms
at the Surface.

Figure 10.

Effect of Evaporator Potential on Apparent Ion Current at Constant Arrival Rate of Atoms to the Surface.

Figure 11.

Effect of Grid Potential on Apparent Ion Currents at Constant Arrival Rate of Atoms at the Surface.

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measured currents, at a constant arrival rate of 7.5×10^{11} atom sec^{-1} , are shown to decrease with increasing evaporator potential. This could have been caused by either 1) a larger fraction of the total secondaries being drawn to the ribbon because of a change in the ratio of the fields dividing the secondary electrons, or 2) an actual increase in the positive ion energy, and hence the number of secondaries, because of a smaller effect of evaporator potential on the grid-ribbon field. Figure 11 shows the effect of grid potential. An increase of the grid-ribbon field would tend to increase the ion energy and hence the number of secondaries. To have separated the secondary electrons from the positive ions at these energies would have required impractically large magnetic fields.

At these arrival rates and under atom evaporation only, the surface was essentially clean above 2400°K and probably under both ion and atom evaporation the surface would be clean above 2300°K. At 2300°K and above, the apparent positive ion current is seen to increase with increasing surface temperature. From Eq. (2) ($\phi - I^*$) must therefore be negative and the ionization potential of uranium must be greater than 4.5 ev. This is not in agreement with Kiess, Humphreys, and Laun's value.⁽⁶⁾ With proper consideration of the secondary electrons and the magnitude of the measured currents one would estimate that the ionization potential of uranium might be only a few tenths of a volt above 4.53 ev.

4. Reflectivity, Emissivity, and Resistivity. During the course of the previous measurements the optical window had been protected by the nickel disc for a short time, after which a uranium deposit was allowed to build up on the inner surface. Impurities of higher vapor pressure, if any, had thus been removed by fractionations before the deposit was allowed to form on the optical surface. The final thickness of the deposit was such that the ribbon at 2600°K could be seen through the film but not measure pyrometrically. A tungsten band lamp was used as a light source and was mounted to present the minimum angle between the source and pyrometer. The reflected image was viewed at an angle of about 5° from the normal. Readings were taken on the reflected image of the band lamp, on the band lamp directly, and on the band lamp through a plate of optical Pyrex of the same thickness as the optical window in the apparatus. Readings were taken in groups of ten measurements which were averaged and carried a probable error of $\pm 0.5^\circ$. Measurements were taken at four different band lamp temperatures. For each calculation of the reflectivity, corrections were applied for the transmissivity of the Pyrex window. From Wien's law and the method of measurement

$$\frac{1}{T_a} + \frac{1}{T} - 2 \frac{1}{T_w} = -\frac{\lambda}{C_2} \ln R = -1.0591 \times 10^{-4} \log R \quad , \quad (8)$$

where T_a is the apparent temperature of the reflected image, T is the temperature of the band lamp measured directly, T_w is the apparent temperature of the band lamp viewed through the Pyrex plate, and λ is the effective wave length of

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the pyrometer, 6650 Å. The average reflectivity at this wave length calculated from all measurements is 0.735 ± 0.015 at 6650 Å. For a deposit of this thickness the spectral emissivity of uranium at 6650 Å = $1 - R = 0.265 \pm 0.015$.

The Drude expression for the reflectivity of metals as a function of the volume resistivity ρ and the wave length λ for the reflectivity of light at a glass-metal interface is

$$R_{\lambda} = 1 - \frac{4\alpha n}{2\alpha^2 + 2\alpha n + n^2} \quad , \quad (9)$$

where $\alpha = \left(\frac{\lambda \times 9 \times 10^{11}}{c \rho} \right)$ for ρ in practical units and $n = 1.474$, the refractive index of Pyrex at 6650 Å. The resistivity of uranium calculated from the reflectivity by Eq. (9) is 22×10^{-6} ohm cm. The average of ten values reported in the literature⁽²⁶⁾ is 31×10^{-6} ohm cm. The ratio of the calculated to the measured resistivities of uranium is very close to the same ratio for plutonium whose reflectivity was measured under similar conditions ($R = 0.53$, $\rho = 96 \times 10^{-6}$ ohm cm).⁽²⁷⁾

III. CONCLUSIONS

Techniques have been established whereby high temperature measurements can be made at background pressures of the order of 10^{-9} to 10^{-10} mm Hg.

The emission constants of uranium were measured by the Richardson method. The value of the work function was found to approach a limiting value of 3.47 ± 0.02 ev and the corresponding A values to approach the theoretical value of $120 \text{ amp cm}^{-2} \text{ deg}^{-2}$.

The ionization potential of uranium was shown to be greater than 4.53 ev by means of surface ionization. From the behavior of the ion currents the value is estimated to be about 4.7 ev.

The reflectivity of a pure and optically flat uranium surface was found to be 0.735 ± 0.015 . The emissivity of uranium was calculated to be 0.265 ± 0.015 . The resistivity of uranium calculated from the reflectivity and the Drude relationship was $22 \mu \text{ ohm cm}$.

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