tests so far available. The general theory of relativity, although profound and exceedingly satisfactory in its epistemological aspects, has so far practically not lent itself to any very obvious and generally impressive applications. This unfortunate discrepancy between the formal beauty of the general theory of relativity and the meagerness of its practical applications makes it particularly desirable to search for phenomena which cannot be understood without the help of the general theory of relativity.

(c) The possibility that cosmic rays originate in supernovae constitutes an added incentive for the continued pursuit of investigations of these extraordinary stars.

My thanks are due to Professor R. C. Tolman, in discussions with whom many of the results given in the first part of this paper were derived, and to Drs. Baade and Minkowski of the Mt. Wilson Observatory in collaboration with whom all of the observational data on supernovae were critically examined on numerous occasions.

APRIL 15, 1939 PHYSICAL REVIEW VOLUME 55

Resistance, Emissivities and Melting Point of Tantalum

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(Received February 20, 1939)

The relation between true and brightness temperatures of tantalum was determined by means of pyrometric observations on the inside and outside of a long thin-walled tube heated electrically. The brightness temperature as a function of heating current was determined by sighting on an electrically heated wire of known diameter. Potential leads of fine tungsten wire welded to tantalum filaments permitted a determination of the electrical properties as a function of temperature. The electrical properties at the melting point yielded a value for this quantity from the extrapolated temperature *vs.* electrical property relations. Value for the melting point determined is 3269°K.

INTRODUCTION

MEASUREMENTS of the resistance, power radiation and brightness temperature of tantalum between room temperature and the melting point are described here. The work was undertaken when certain inconsistencies with previously published data for tantalum were discovered during experiments on the rate of evaporation of this metal which are described in an accompanying paper.[1] The relationship between resistivity and power radiation which was observed during this work is not the same as that published by Worthing.[2,3] For a given value of power radiation the specific resistance reported here is about four percent lower than Worthing's value. It seems probable that the constitution of tantalum as made today may differ from that of the product available at the time of the earlier work. Forsythe and Watson[4] have reported an apparent change in the properties of tungsten which took place in an unexplained manner between 1922 and 1934. The earlier values of resistivity were the higher. Tantalum apparently has undergone a similar type of change.

Brightness temperature observations were also made, and are in good agreement with the earlier work both of Worthing and of Utterback and Sanderman.[5] An apparent disagreement between the latter two experimenters is due to a discrepancy between the data as shown in the table and in one of the graphs of Worthing's paper.

Except where noted the tantalum used in these experiments was regular stock from the Fansteel Metallurgical Corporation.

[1] D. B. Langmuir and L. Malter, Phys. Rev. **55**, 748 (1939).
[2] A. G. Worthing, Phys. Rev. **28**, 190 (1926).
[3] A. G. Worthing, Phys. Rev. **28**, 174 (1926).
[4] W. E. Forsythe and E. M. Watson, J. Opt. Soc. Am. **24**, 114 (1934).
[5] C. L. Utterback and L. A. Sanderman, Phys. Rev. **39**, 1008 (1932).

Procedure of Measurement

1. Brightness *vs.* true temperature

A blackbody with tantalum walls was made by rolling a narrow strip of two-mil tantalum sheet into the form of a cylinder 0.065 inch in diameter and four inches long. The edges were overlapped but not welded because it had previously been found that welding resulted in a non-uniform temperature distribution around the circumference. A number of 0.010-inch holes were drilled at various points in the middle portion of the cylinder. These served as blackbodies for the determination of the true temperature. The current leads were made of tantalum strip so proportioned as to minimize lead loss. The temperature of the cylinder was uniform over about 80 percent of its length at the lowest temperature studied.

This structure was sealed into a glass bulb and baked on exhaust at 450°C for 30 minutes. The tantalum was then outgassed by heating to 1750°K for 14 hours and by subsequent flashing for several 20-second intervals at 2600°K. After this processing, the cylinder was removed from the bulb and sealed into a new clean bulb. The purpose of this procedure was to minimize light absorption which would be due to tantalum evaporated during outgassing. The new assembly was baked at 450°C for 14 hours and the tantalum outgassed at 1750°C for five hours with seven, interposed, 30-second flashes at 2400°C. A barium getter was exploded before seal-off.

True temperatures and brightness temperatures were determined by sighting first with a telescopic, disappearing filament type of pyrometer obliquely into one of the holes, and then upon the external surrounding region. Current through the pyrometer filament was measured with a Leeds & Northrup Type K potentiometer and standard resistance. The pyrometer was calibrated by means of a wide-strip, tungsten filament lamp which was subsequently calibrated by the National Bureau of Standards for the effective wave-length $\lambda_e=0.652\mu$. At temperatures in excess of 1800°K, an amber filter was used to reduce the observed brightness; the actual true and brightness temperatures were obtained from the values with the filter interposed by means of the relation

$$1/T_A-1/T_0=\lambda_e \log \tau/0.434C_2=A, \quad (1)$$

where T_A is the brightness temperature, degrees Kelvin; T_0 is the apparent brightness temperature, viewed through amber filter, degrees Kelvin; C_2 is the Wien-Planck constant, 1.433 cm·degrees; and τ is the transmission of the filter at the wave-length of observation. This equation follows directly from Wien's law of radiation. The filter constant A was determined by the National Bureau of Standards for the combined amber and red eyepiece filters. The effective wave-length of the red filter was $\lambda_e=0.674\mu$. All calibrations were corrected so as to apply to $\lambda_e=0.665\mu$.

Several runs were taken with ascending and descending temperature values at two of the holes, but with no variation in results greater than the experimental error. The observed temperature values T_1 were corrected for the effects of wall and film absorption in accordance with the relation

$$1/T_1-1/T_0=-0.0076\times10^{-3} \text{ degree}^{-1}.$$

The indicated value was determined experimentally after cracking open the bulb. Since this correction applies to both true and brightness temperatures, it has practically no effect on the relation between the two temperatures.

2. True temperature *vs.* heating current

A 0.012-inch tantalum wire 10 centimeters long was mounted in a bulb provided with a flat Pyrex window. Means were provided for interposing a nickel disk between the filament and window to prevent evaporation from the former depositing on the latter during exhaust. The assembly was baked on exhaust at 450°C for one hour and the filament outgassed by heating to 2300°K for 30 minutes and then to 2465°K for four minutes. A getter was exploded and the tube sealed off.

No appreciable lead loss occurred at the midpoint of this filament throughout the range studied. Brightness temperature observations as a function of current were taken in the manner indicated in the preceding section. The current values were measured with the Leeds & Northrup potentiometer. Readings were taken at suc-

cessively higher temperatures. When temperatures in excess of 2000°K were attained, the current was dropped to the value corresponding to 1750°K for a check reading before progressing to the next higher value. In this way any change due to evaporation could be detected. Actually, each reading up to the highest temperature (2952°K) used was made with sufficient rapidity so that no effect due to evaporation was observed.

A section of the filament was then weighed, and its diameter computed, by using the value 16.60 g/cm³ for the density. From these results the brightness temperature of a tantalum wire as a function of the current traversing it can be obtained.

3. Electrical properties

Eight tubes were built with tantalum filaments ranging from 0.005 inch to 0.020 inch in diameter. Each was provided with 0.002-inch tungsten potential leads. One of these tubes was built with 0.005-inch tantalum wire made in Austria about 1932. These tubes were baked for one hour at 450°C, and then the filament was outgassed for one hour at 2300°K followed by short flashes at about five minutes at 2465°K and one minute at 2630°K. Four of these tubes contained 0.012-inch diameter filaments which had previously

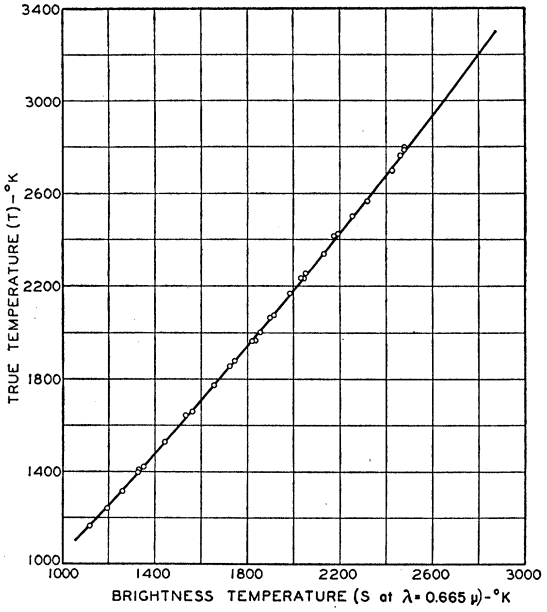

FIG. 1. True temperature T *vs.* the brightness temperature S for the effective wave-length $\lambda = 0.665\mu$.

TABLE I. *Data on resistance, emissivity, and thermal expansion of tantalum. T is the true temperature; ρ is the resistivity corrected for thermal expansion; W is the total radiation intensity not corrected for thermal expansion and e_t is the power emissivity corrected for thermal expansion; M and L are the results of Malter and Langmuir; W are those of Worthing, and U and S those of Utterback and Sanderman. The spectral emissivity at 0.665μ is indicated by $e_{0.665\mu}$. The thermal expansion given by Worthing is designated by l/l_0.*

T °K	ρ OHM·CM	W WATTS/CM²	e_t	A'	V'	$V'A'^{\frac{1}{3}}$	BRIGHTNESS TEMPERATURE M AND L	W	U AND S	$e_{0.665\mu}$	l/l_0
1000	44.1	0.793	0.136	211	0.0118	0.0702	967	966		0.481	1.0047
1100	47.3	1.23	.144	254	.0152	.0963	1060			.476	1.0055
1200	51.0	1.84	.153	299	.0193	.1291	1152	1149		.469	1.0063
1300	54.8	2.73	.163	352	.0244	.1723	1242		1250	.462	1.0071
1400	59.0	3.95	.174	408	.0304	.2255	1332	1329	1337	.456	1.0079
1500	62.4	5.47	.184	469	.0368	.2855	1421			.449	1.0087
1600	65.8	7.36	.194	528	.0438	.3540	1508	1506	1508	.442	1.0095
1700	69.3	10.10	.205	602	.0527	.4450	1596			.437	1.0103
1800	72.5	13.28	.215	676	.0617	.5415	1682	1682	1678	.432	1.0111
1900	75.8	17.12	.223	751	.0716	.6508	1767			.426	1.0119
2000	78.9	21.63	.232	828	.0821	.7709	1852	1851	1843	.421	1.0127
2100	82.0	27.11	.240	910	.0936	.9071	1933		1926	.417	1.0135
2200	85.2	34.18	.247	1002	.1072	1.080	2018	2018		.413	1.0144
2300	88.3	42.23	.254	1095	.1212	1.250	2099			.409	1.0152
2400	91.3	51.27	.261	1189	.1357	1.437	2181	2181		.405	1.0161
2500	94.4	62.38	.269	1288	.1522	1.656	2261			.402	1.0170
2600	97.4	75.37	.276	1394	.1699	1.898	2341	2339		.400	1.0179
2700	100.2	89.89	.282	1502	.1880	2.153	2421			.397	1.0188
2800	102.9	105.5	.288	1606	.2064	2.417	2499	2495		.394	1.0197
2900	105.6	123.0	.293	1715	.2257	2.699	2575			.391	1.0206
3000	108.7	144.4	.298	1830	.2479	3.032	2652	2647		.388	1.0216
3100	111.4	167.4	.302	1948	.2700	3.367	2727			.386	1.0225
3200	113.9	194.2	.306	2075	.2940	3.749	2803			.384	1.0235
3269	115.5	214.5	.309	2164	.3110	4.025	2855			.383	1.0242

been aged at 2300°K for over 72 hours in a separate bulb.

Repeated voltage *vs.* current runs were made on all these tubes. In addition, points for the volt-ampere characteristic were obtained at the beginning and end of the runs on about twenty similar 0.012-inch diameter filament tubes used for the evaporation study.

Results

1. Brightness *vs.* true temperature

In Fig. 1 are plotted the final results. The compiled data for the present determination, as well as those of Worthing,[3] and of Utterback and Sanderman,[4] are shown in Table I. The results are in excellent agreement with those of Worthing[2] but differ slightly from the later values of Utterback and Sanderman.

The curve of Fig. 1 can be represented over the range of experimental points by

$$T=0.9919S+37.14\times10^{-6}S^2+5.74\times10^{-9}S^3 \quad (2)$$

where S is the brightness temperature. The percentage error at any point is less than 0.5 percent.

This equation has been used to extrapolate the temperature scale curve to higher values for a determination of the melting point.

The spectral emissivity $e_{0.665\mu}$ as a function of T was determined from the curve of Fig. 1 by means of the relation

$$1/T-1/S=\lambda_e \log e_{0.665\mu}/0.434C_2.$$

The values were plotted and a smooth curve drawn through them. The values obtained from the smooth curve are given in Table I. The probable error of emissivity values is 0.01.

2. True temperature *vs.* heating current

The average results obtained in the manner described above are given in Table I, together with some values of Worthing. The heating current, in this case, is expressed in terms of A' where $A'=A/d_0^{\frac{3}{2}}$, $A=$the heating current, and $d_0=$the filament diameter at room temperature. While the probable error in any series of measurements on any single tube is about 0.2 percent, a spread of as much as 1.0 percent occurs between different samples of tantalum.

The spread in these values as well as the deviations from Worthing's values are very likely due to differences in the purity of the tantalum. This will be discussed in greater detail below.

3. Electrical properties

From the measured values of voltage and current, the resistivity and power radiation per cm^2 of tantalum were determined throughout the temperature range. The determined values were corrected for thermal expansion in accordance with the expansion data of Worthing.[4] The average values are included in Table I. In this case, too, the spread between different tubes is about 1.0 percent.

It was found that if the filament was heated in a partial pressure of air, the difference of potential across the potential leads was increased for a given value of heating current. Further heat treatment in vacuum did not restore the original values.

This fact indicates that Worthing's values which deviate in the same direction (but to a considerably greater extent) may have been obtained with less pure tantalum. That such was the case appears reasonable since the tantalum he used was made prior to 1914 and very likely inadequately "purged" during manufacture, because of the newness of the art.

The concordance of the values for the Austrian tantalum made in 1932 with those for the Fansteel product further indicates the relative purity of the present day product. Further information bears out this view. Thus, for example, the authors' value for resistivity at 300°K of 13.85×10^{-6} ohm·cm, which is lower than Worthing's value of 14.6×10^{-6} ohm·cm, is evidence of the greater purity of present day stock.

The resistivity between 0°C and 100°C can be expressed by

$$\rho=(12.56+0.048T°\text{C})\times10^{-6} \text{ ohm·cm}.$$

4. Total emissivity

The total emissivity e_t was determined from the data of Table I by means of the Stefan-Boltzmann law. These values are included in Fig. 1.

In addition, in Table I are included values of V' and $V'A'^{\frac{1}{3}}$. These, together with values of A', are of use in the design of filaments of circular cross section for particular applications, and are defined as follows:

$$V' = Vd_0^{\frac{1}{2}}/l_0, \quad V'A'^{\frac{1}{3}} = VA^{\frac{1}{3}}/l_0,$$

where V is the measured difference of potential, d_0 is the filament diameter at room temperature, and l_0 is the distance between the potential leads at room temperature.

It is of interest to note that while the use of V' or A' as determined from Worthing's data would lead to a disagreement in temperature values, the use of Worthing's values for power radiation or $V'A'^{\frac{1}{3}}$ lead to temperature values only slightly different from those of the authors. These results indicate that the presence of small quantities of impurities affect the resistivity, but not the radiation from tantalum at a given temperature.

It should be noted that the quantities A', V', $V'A'^{\frac{1}{3}}$, and W as given in Table I are not corrected for the expansion of tantalum, but are given in terms of the dimensions at 25°C. In order to permit of their correction in cases desired, the values of l/l_0 as determined by Worthing[3] are included in the table. However, the total emissivity e_t has been computed on the basis of corrections for expansion.

Melting point

The melting point of tantalum was determined by measuring the current at which a filament of known diameter burned out. Eight samples of wire of varying history were tried, and the currents at burn-out were the same within two parts in one thousand. No difference was found due to the position in which the filament loop hung. When mounted with the loop up, the filament crumpled and collapsed along several centimeters of its length. This fact combined with the reproducible values of current indicate that the determination is accurate to 0.2 percent with respect to current.

The value of A' at the melting point is 2164 amp./cm$^{\frac{3}{2}}$, and corresponds to the temperature 3269°K.

Surface structure

The appearance of the tantalum surfaces when viewed with a microscope differed somewhat from one sample to another. The outside of the hollow cylinder which formed the blackbody had a high polish and showed no scratches or roughness. A network of grain boundaries was visible, but this could not be discerned through the pyrometer. The condition of the filament surfaces depended upon the amount of aging at a high temperature which the wire had undergone. Longitudinal scratches initially present due to the drawing process smoothed out upon aging so that ultimately the surface consisted of polished, rounded, individual grains whose diameters were approximately one-tenth that of the filament. The die marks and grain boundaries both were visible under a microscope during the brightness-temperature observations which were made at a stage midway in the aging process.

When such a surface was viewed through the pyrometer, details of the surface could be seen. Ability to see the details indicated that the emissivity varies from point to point over the surface. The average emissivity, however, does not seem to be materially affected by the progressive changes in surface structure, since the volt-ampere characteristics of the filaments prove to be unaffected by aging. All aging processes were carried out using alternating current. Direct-current heating produces radical changes in the form of the surface as has been shown by Johnson.[6]

The writers are indebted to Dr. H. J. Miller for supplying a sample of Austrian-made wire, to T. B. Perkins for assistance in setting up the pyrometric apparatus, and to V. K. Zworykin and B. J. Thompson for their interest and counsel.

[6] R. P. Johnson, Phys. Rev. **54**, 459 (1938).