A TEMPERATURE SCALE FOR TUNGSTEN

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ABSTRACT

Temperature variation of the resistance of tungsten from 273°K to 3655°K.—In the range from 273°K to 1500°K measurements were made of the resistance of coils of pure, well-aged, tungsten filaments (diam. 2.61 mils) placed in the center of a constant temperature compartment of an alundum resistance furnace through which a stream of pure dry hydrogen was continuously passed. Temperatures were measured by a carefully standardized chromel-alumel thermocouple. In the range 1200°K to 3655°K tungsten filaments (V shape, length 40–50 cm, diam. 2.61, 5.00 and 9.85 mils) were mounted in lamp bulbs and their resistances measured. Temperatures were determined by pyrometering against a standard lamp. The specific resistance of tungsten was found to vary from 5.00×10^{-6} ohm cm at 273°K to 117.1×10^{-6} at 3655°K.

Temperature variation of the rate of radiation from tungsten filaments.—Lamps of the above type were also used to determine the variation with temperature of the energy radiated per cm² of the tungsten filaments. Temperatures from 300°K to 1500°K were measured by the resistance method, from 1500°K to 3655°K by the optical pyrometer. The rate of radiation varied from .000016 watts/cm² at 300°K to 399.4 at 3655°K.

A LARGE number of investigations on electrical discharges in gases involve the use of a "cold" cathode whose temperature is less than 1500°K. Since temperatures cannot be estimated with any great accuracy in the range 1500°K to 273°K by the usual pyrometric or photometric methods, the resistance method of determining temperatures finds valuable application here. In this paper a temperature scale for pure tungsten, based primarily upon accurate resistance measurements, is presented for the range 273°K to 1500°K. For the sake of completeness the measurements are continued up to 3655°K and observations are made on the rate of radiation from tungsten filaments for the temperature range 300°K to 3655°K.

The ratio of the resistance at the temperature T to that at 0°C, or at a known room temperature, affords a simple and convenient estimate of the temperature of tungsten filaments. If ρ is the resistivity of tungsten in ohm cm at the temperature T, the resistance R of a cylindrical filament at this temperature will be $4\rho l/\pi e^2$, where d and l are expressed in cm. Putting $R' = 4\rho/\pi$, we have $R' = Rd^2/l$. R', the resistance of a filament of unit length and unit diameter is a function of the temperature alone and may be used as a measure of the temperature.

The resistance method of measuring temperatures has the advantage that it can be used when the filament is surrounded by a gas or when its surface is tarnished by oxidation. On the other hand it has the disadvantage that the resistance and its temperature coefficient are very sensitive to traces of impurities, and also that at low temperatures the resistance of a filament is often so low that errors due to lead and contact resistances are apt to play a large role.

Measurements of the ratio of hot to cold resistance of tungsten have been made by Somerville,[1] Pirani,[2] Langmuir,[3] Holborn,[4] Forsythe and Worthing,[5] and Zwikker.[6]

Measurements of the Ratio of Hot to Cold Resistance

Three different tungsten wires were used, all drawn from the same rod of metal which was of unusual purity. The wires, which we will designate W_1, W_2 and W_3 were 2.61, 5.00 and 9.85 mils in diameter, respectively. The diameters were determined from the density and the weight per unit length, using the value 19.35 gm/cc which has been accepted for the density of well aged, pure tungsten. This value has been determined at the Phillips Glowlamp Works in Holland[7] from an extensive series of density measurements on aged tungsten filaments. (It is interesting to note that the latest x-ray work on single crystal tungsten gives a value of $19.32 \pm .02$ as an upper limit for the density, while experimental measurements on the wires used in the present work gave 19.39.) The diameters obtained by the above method agree within the experimental error with the results of a series of measurements made with a sensitive micrometer.

Several lengths of the wire W_1 (each having a resistance of approximately 8 ohms at 0°C) were coiled on a 10 mil mandrel; each length was electrically welded to 30 mil molybdenum leads and sealed into a bulb. These lamps were then well exhausted (residual gas pressure less than 0.0006 bar), the glass being baked out at 360°C while the filaments were heated for about 5 minutes at 2800°K. After seal-off the coils were further aged by heating to 2400°K for twenty-four hours. They were then removed from the bulbs and used for the subsequent resistance measurements.

[1] A. A. Somerville, Phys. Rev. **30,** 433 (1910).
[2] Pirani, Verh. d. Phys. Ges. **12,** 301 (1910); Phys. Zeits. **13,** 753 (1912).
[3] Langmuir, Phys. Rev. **7,** 302 (1916).
[4] Holborn, Ann. d. Physik **59,** 145 (1919).
[5] Forsythe and Worthing Astrophys. J. (Jan. 1925).
[6] Zwikker, Koninklijke Akademie Van Wetenschappen Te Amsterdam Deel 34, No. 5.
[7] Private communication.

In this case the coils were welded to 120 mil Mo leads and correction made for the resistance of the latter by making a separate determination of the resistance of similar Mo leads.

The resistance of the coil at 0°C measured by the Wheatstone bridge method was obtained before and after a set of data by immersing in well stirred distilled water maintained at 0°C by a surrounding ice and salt bath. To obtain values of the hot resistance, the coiled filament was placed in the center of a constant temperature compartment which in turn was placed in the center of the alundum tube in a resistance furnace through which a constant slow stream of pure dry hydrogen was continuously passed.

The constant temperature compartment consisted of two alundum discs spaced 4 inches apart and held firmly in position by means ofl heavy molybdenum wires passing through them, while a cylindrica molybdenum shield co-axial with the alundum furnace tube and having one half inch clearance from it fit snugly between them. As a precautionary measure, two radiation shields were placed at equal distances from each end of the central heating compartment, six being used altogether to divide the furnace tube into zones. It was observed that for any constant setting of the current through the resistance coil of the furnace the temperature at any point within the central compartment was constant.

The temperature was determined by the potential difference, as measured on a potentiometer, between the hot and cold (0°C) junctions of a well-aged chromel-alumel thermocouple. The latter was calibrated before and after a set of data against a well aged standard platinum, platinum-rhodium couple.

The curve for the platinum couple was obtained by calibrating against a newly standardized Bureau of Standards platinum couple while the melting points of the purest obtainable tin, aluminum, gold and copper were also used for fixed points at which the thermocouple millivolts and the resistance of the tungsten coil were measured simultaneously in the hydrogen furnace. The thermocouple was also checked at the gold point in air immediately after each set of measurements.

Hot resistance measurements were obtained on a number of different coils both on the ascending and descending temperature curves with the temperature in the central heating compartment brought to a constant value for each reading.

As a check on the accuracy of the data obtained in the hydrogen furnace, resistance data were obtained on some coils up to 250°C in an oil bath. These data agreed well with those from the furnace measurements.

The resistivity of tungsten at 0°C was obtained from measurements on a number of coils by the Wheatstone bridge method and also from measurements on straight pieces of each of the well aged wires W_1, W_2 and W_3 by the current voltage method using a laboratory standard potentiometer. The value obtained at 0°C expressed as the resistance of a cylindrical wire 1 cm long and 1 cm in diameter agrees with Langmuir's value, i.e.,

$$R' = 6.37 \times 10^{-6} \pm .01$$

The results of the measurements, expressed in terms of the function R', were plotted on a large scale against temperature and the most probable curve drawn through the data. The data from all the coils measured were found to lie very closely along this smooth curve from which the data in the table were obtained.

The data for the resistivity of tungsten were then used to estimate the temperatures in a determination of the energy radiated in watts per unit area of surface for the range 1500°K to 293°K.

Three lamps, each of which had a cocoanut charcoal side tube attached, which was immersed in liquid air to insure good vacuum, were used for this experiment. The lamps contained two V-shaped filaments, one 40 cm and the other 50 cm long of W_1, W_2 and W_3 wires respectively. The filaments were arc-welded to equal lengths of 40 mil molybdenum leads, and were degassed and aged according to the schedule described previously.

The volt-ampere characteristics were measured for the two different lengths of each size of filament and the watts radiated per unit area calculated by the method of differences to eliminate lead losses. This method was found to be more consistently reproducible than that involving the use of fine wire potential leads welded to a measured length of filament (although this method was also used in several check experiments).

Direct experimental determinations of the watts radiated per cm^2 were thus obtained down to 600°K below which temperature errors due to lead losses could not be eliminated. The watts radiated per cm^2 below 600°K were calculated by the method of Davisson and Weekes.[8] The complete data expressed as watts input necessary to maintain one cm^2 of tungsten at the temperature T are given in the table.

[8] Davisson and Weekes, J.O.S.A. **8** (May, 1924).

These same lamps were subsequently used to measure the watts radiated per unit area and the resistivity of tungsten in the range 1200° to 3000°K. The filament temperatures, at which the electrical characteristics were obtained for the two lengths of each wire, were estimated by pyrometering against a standard lamp. This lamp was

TABLE I

Resistance and radiation data on tungsten filaments. R' is the resistance of a filament 1 cm long and 1 cm in diam.; ρ is the specific resistance in ohm cm; W' is the number of watts radiated from 1 cm length of a filament 1 cm in diam.; W is radiation from the surface in watts per cm.^{2}

The data are based on filament dimensions measured at room temperature.

	Jones				Zwikker		Forsythe and Worthing	
T°K	$R'+10^6$	W'	$\rho+10^6$	W	$\rho+10^6$	W	$\rho+10^6$	W
273	6.37	0.0	5.00	0.0	.....	......	......	......
293	6.99	0.0	5.49	0.0	.....	......	......	......
300	7.20	0.0000501	5.65	0.000016	.....	......	......	......
400	10.26	0.00619	8.05	0.00197	.....	......	......	......
500	13.45	0.0304	10.56	0.00970	.....	......	......	......
600	16.85	0.0953	13.23	0.0304	.....	......	......	......
700	20.49	0.240	16.10	0.0764	.....	......	......	......
800	24.19	0.529	18.99	0.169	.....	......	......	......
900	27.94	1.04	21.94	0.331	.....	......	......	......
1000	31.74	1.89	24.90	0.602	.....	......	......	......
1100	35.58	3.24	28.10	1.030	.....	......	......	......
1200	39.46	5.24	31.96	1.67	30.9	1.70	32.02	1.70
1300	43.40	8.10	34.10	2.58	34.0	2.70	35.24	2.60
1400	47.37	12.1	37.18	3.86	37.1	3.94	38.52	3.86
1500	51.40	17.4	40.35	5.54	40.2	5.52	41.85	5.61
1600	55.46	24.4	43.50	7.77	43.4	7.90	45.22	7.86
1700	59.58	33.3	46.78	10.6	46.7	10.7	48.63	10.73
1800	63.74	44.4	50.00	14.2	49.9	14.1	52.08	14.46
1900	67.94	58.2	53.30	18.6	53.2	18.6	55.57	18.6
2000	72.19	75.0	56.67	23.9	56.7	24.0	59.10	24.1
2100	76.49	95.1	60.00	30.3	60.1	30.5	62.65	30.4
2200	80.83	119.0	63.40	37.9	63.5	38.2	66.25	38.1
2300	85.22	147.2	66.85	46.8	66.9	47.2	69.90	47.0
2400	89.65	179.9	70.38	57.3	70.5	57.3	73.55	57.0
2500	94.13	217.4	73.83	69.2	74.0	69.4	77.25	69.2
2600	98.66	260.6	77.38	83.0	77.6	83.5	81.0	83.0
2700	103.2	310.1	81.00	98.8	81.2	100.5	84.7	98.9
2800	107.9	366.4	84.69	116.7	84.8	119.0	88.5	116.5
2900	112.5	430.3	88.30	137.2	88.5	139	92.3	136.5
3000	117.2	502.6	92.00	160.1	92.3	162	96.2	159.6
3100	122.0	583.9	95.74	186.1	97.0	189	100.0	184.2
3200	126.8	675.2	99.55	215.0	99.9	221	103.8	211
3300	131.6	777.5	103.3	247.6	103.8	254	107.8	242
3400	136.5	891.9	107.2	284.0	107.8	291	111.7	276
3500	141.4	1020	111.1	325.0	.....	......	115.7	314
3600	146.4	1164	115.0	371.0	.....	......	......	......
3655	149.2	1253	117.1	399.4	.....	......	121.8	376

standardized through the kindness of Dr. W. E. Forsythe of the Nela Research Laboratory, to whom I am further indebted for checking temperatures and electrical characteristics on several of the experimental lamps.

The temperature scale used in the pyrometrey determinations is one recently adopted by the General Electric Company's research laboratories. On this scale the gold point is the Day and Sosman[9] value of 1336°K and C_2 of Wien's equation is taken as 1.433 cm deg. (the value adopted for the forthcoming International Critical Tables). On this scale the palladium point is 1829°K,[10] and the melting point of tungsten comes out to be 3655°K.[5]

Worthing's determination[11] of the spectral emissive power for tungsten, upon which the standard lamp temperatures were based has been independently verified by Zwikker.[6]

Zwikker's comprehensive paper was published subsequently to the completion of our work. The values given by him for watts radiated and resistance are tabulated in columns 6 and 7 in the table. The agreement with our values is excellent in the temperature range in which the efforts were duplicated.

Forsythe and Worthing[5] have recently published a summary of the properties of tungsten as a function of temperature. Their values for the watts radiated and the resistivity of tungsten are also given in columns 8 and 9 in the table. Since their values for the resistivity of tungsten are somewhat higher than the more recent determinations by Zwikker, and the writer (compare values in Table I) new values for the various functions which have been found convenient for estimating the temperature of tungsten filaments will be published in the near future in the General Electric Review.

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[9] Day and Sosman, Amer. Jour. of Sci. **29**, 93 (1910).
[10] Hyde and Forsythe, Astrophys. J. **51**, 244 (1920).
[11] Worthing, Phys. Rev. **10**, 377 (1917).