Physics. — *"The characteristics of tungsten and the candle power of the black body"*. By C. ZWIKKER. (Communicated by Prof. P. ZEEMAN).

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The importance of tungsten for the glowlamp and radio industry, as well as the scientific interest we have in an extensive knowledge of the physical properties of a material, which may be obtained in a very pure state, have lead me to a redetermination of the diverse properties of this metal at high temperatures. The final results have been collected in table I.

The temperature has been measured by an optical pyrometer method, making use of PLANCK's radiation law. The value of C_2 which occurs in this formula is taken as 14 330 μ degr. The basispoint used for the temperature scale is the melting point of gold, for which the value of 1336° KELVIN is adopted. The melting point of the sample of gold, used by me, which was kindly supplied to us by Dr. V. HETEREN, was in concordance with the goldpoint of the Physikalisch Technische Reichsanstalt.

The spectral emissivity has been determined by comparing the inner and outer brightness of a tungsten rod in which a hole had been drilled and which was raised to a high temperature by different methods. With this so determined spectral emissivity e_λ, the true temperature T has been calculated from the observed „brightness temperature" S by the relation:

$$\frac{1}{T}-\frac{1}{S}=\frac{\lambda\, 2{,}303 \log e_\lambda}{C_2}.$$

Electrical measurements have been performed by a compensation method. The standard resistance and the standard element had been verified by the P.T.R. The *resistivity* was obtained from the electrical resistance of a tungsten filament of known dimensions; the *total radiation* from the wattage input of this filament.

Corrections have been made for the cooling at the filament junctions.

The brightness given in the table is the normal candle power, expressed in International Candles. The photometric standard lamps had been standardized by the P. T. R. in 1922. The candle power was given by the P. T. R. in Hefner Candles and was converted by us to International Candles, assuming that:

$$1\ I.C. = 1{,}11\ H.C.$$

TABLE I. The characteristics of tungsten.

Temperature	Spectral emissivity $\lambda = 0.665$	Brightness temperature $\lambda = 0.665$	Colour temperature	Resistivity	Total radiation	Brightness	Thermionic emission	Rate of vaporization	Thermal conductivity	Thomson-effect
T	e_λ	S_λ	T_c	ρ	η	B	i	m	k	σ
1200	0.458	1150	1210	30.9	1.70	0.0071				
1300	0.456	1240	1312	34.0	2.70	0.0311				
1400	0.454	1331	1414	37.1	3.94	0.117				
1500	0.451	1421	1517	40.2	5.52	0.370	$0.102.10^{-6}$	$1.78.10^{-22}$		
1600	0.449	1510	1619	43.4	7.90	1.07	$0.102.10^{-5}$	$1.78.10^{-20}$		
1700	0.446	1597	1722	46.7	10.7	2.62	$0.812.10^{-5}$	$1.02.10^{-18}$		
1800	0.444	1685	1825	49.9	14.1	5.75	$0.490.10^{-4}$	38.0	1.22	—18
1900	0.442	1773	1929	53.2	18.6	12.3	$0.257.10^{-3}$	932	1.26	—20
2000	0.440	1859	2033	56.7	24.0	23.2	$0.112.10^{-2}$	$15.5\ .10^{-15}$	1.29	—22
2100	0.438	1945	2137	60.1	30.5	42.4	0.00427	214	1.31	—24
2200	0.435	2028	2242	63.5	38.2	72.0	0.0141	$2.24.10^{-12}$	1.33	—26
2300	0.432	2111	2347	66.9	47.2	116.5	0.0437	19.5	1.35	—28
2400	0.430	2193	2452	70.5	57.3	185	0.123	138	1.37	—30
2500	0.427	2275	2557	74.0	69.4	279	0.302	833	1.39	
2600	0.424	2357	2663	77.6	83.5	409	0.776	$4.17.10^{-9}$	1.405	
2700	0.422	2437	2770	81.2	100.5	598	1.74	20.4	1.42	
2800	0.420	2517	2878	84.8	119.0	823	3.74	83.3	1.43	
2900	0.417	2596	2986	88.5	139	1110	7.57	309		
3000	0.415	2675	3094	92.3	162	1490	14.9	$1.05.10^{-6}$		
3100	0.413	2753	3202	97.0	189	1960	28.1	3.31		
3200	0.411	2829	3311	99.9	221	2530	50.5	10.0		
3300	0.409	2903	3422	103.8	254	3250	87.7	26.3		
3400	0.407	2978	3533	107.8	291	4080	149	70.8		
degr. K		degr. K	degr. K	$\mu\Omega$ cm	Watts cm $^{-2}$	I.C. cm $^{-2}$	Amp. cm $^{-2}$	gr. cm $^{-2}$ sec. $^{-1}$	Watts cm $^{-1}$ degr. $^{-1}$	μV.degr. $^{-1}$

For the purpose of measuring the *thermionic emission* lamps were constructed in which the filament was surrounded by an electrode in the usual manner. A positive charge given to this electrode collected the emitted electrons. The electron emission is given by the formula:

$$i = AT^2 e^{-\frac{b}{T}} \text{ Amp.}/_{cm^2}$$

in which

$$A = 60{,}2$$
$$b = 52230.$$

The rate of vaporization has been determined from the decrease in diameter of a glowing tungsten filament maintained at a constant temperature, as calculated from the increase of its resistance, measured as a function of time. For the rate of vaporization the following formula holds:

$$\log m = 11{,}92 - \frac{4.84.10^4}{T} - 0{,}368 \log T - 0{,}00016\, T.$$

From the observed temperature variation near the leads, *heat conductivity* determinations were made. The positive and the negative filament end showed a somewhat different temperature variation. This is caused by the *Thomson effect*; the Thomson coefficient can be calculated from the ratio of the temperature gradients at both leads.

The *colour temperature* of tungsten at a temperature T is defined as

TABLE II. The candle power of the black body

T	B
1300	0.015
1336	0.111
1400	0.261
1500	0.818
1600	2.26
1700	5.74
1800	12.4
1900	25.7
2000	50.1
2100	91.6
2200	156
2300	256
2400	410
2500	620
2600	915
^oK	I.C./cm^2

the temperature of the black body to obtain the same energy distribution in the visible spectrum as tungsten gives. The colour temperature is of great importance because of the possibility to calculate the candle power of the black body from the relation between brightness temperature, colour temperature and candle power of tungsten by the formula:

$$B_{\text{Black Body at } T_c} = B_{\text{Tungsten at } S} \cdot e^{\frac{C_2}{2{,}303\,\lambda}\left(\frac{1}{S} - \frac{1}{T_c}\right)}.$$

Furthermore direct candle power determinations have been done of the black body. In this study the pyrometer bench was used as a microphotometer, it being standardized for white as well as for red (monochromatic) light. The red and the white brightness of the black body were measured in immediate succession, the red brightness determining the temperature. These measurements extended over the temperature range from 1300 to 2600° K, and were in complete concordance with the brightness measurements of tungsten filaments. Our data on the candle power of the black body are given in table II.

These measurements give for the least mechanical equivalent of light the value:

$$M = 0{,}00146 \text{ Watts per Intern. Lumen.}$$

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Natuurkundig Laboratorium der
N.V. PHILIPS' *Gloeilampenfabrieken.*