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DERIVATION OF PHOTOMETRIC STANDARDS FOR TUNGSTEN-FILAMENT LAMPS

By H. T. Wensel, Wm. F. Roeser, L. E. Barbrow, and F. R. Caldwell

ABSTRACT

A method is described for comparing the candlepower of carbon lamps with that of tungsten lamps which avoids the usual difficulties of heterochromatic photometry. The method is based on photometric comparisons of carbon lamps with a black body immersed in freezing platinum and of gas-filled tungsten lamps with a black body immersed in freezing iridium. The relative integral brightness of the two black bodies is calculated from the ratio of brightness measured at one wave length with an optical pyrometer.

The method was used to calibrate six tungsten-filament gas-filled standard lamps, operating at a color temperature of 2,727 K, on the basis of the carbon primary standards, which operate at a color temperature of 2,097 K. The step-up as made is applicable to the International Commission on Illumination standard observer with an accuracy certainly better than 1 percent. A comparison with the vacuum tungsten standards maintained at the National Bureau of Standards since 1911, yielded results agreeing within 1 percent.

An empirical formula is given for the brightness of a black body over the range 1,550 to 2,727 K.

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I. INTRODUCTION

The unit of luminous intensity is defined in terms of the average light emission, in a specified horizontal direction, of a number of carbon-filament incandescent lamps each operating at a specified voltage. Groups of such standards of horizontal candlepower are in the custody of the several national standardizing laboratories and periodic intercomparisons have indicated that there are no discrepancies of more than a few tenths of a percent among these various groups. If, therefore, these standards are changing with time, the various groups are changing at substantially the same rate. It is believed that the drift in the unit, up to the present time, has been small.

Practically all lamps now in commercial use are tungsten lamps of either the vacuum or gas-filled type. The spectral-energy distribu-

tion of the light from these lamps differs from that of the light from the carbon-filament standards chiefly because of the higher filament temperatures. For rating tungsten lamps, the various national standardizing laboratories maintain tungsten-filament auxiliary standards, which have been "stepped-up" from the carbon standards. This step-up has been made independently in each country and the resulting tungsten standards of the various national laboratories are not in good agreement. This condition is traceable to the difficulties of heterochromatic photometry involved.

The unit of light is of such a nature that, when defined for light of a given quality or spectral distribution, an additional specification of the characteristics of the observer's eye is required before the unit can be used to evaluate light of any other quality. This specification is accomplished by selecting a set of factors which express the relative visibility of radiation of the various wave lengths for a selected (hypothetical) observer.

The visibility of radiant energy was measured by Gibson and Tyndall [1] for 52 observers; their recommended average values, taking into account previous work as well as their own have been used by the International Commission on Illumination to define a standard [2] observer. All actual observers depart more or less from this definition. As an illustration consider the two observers designated by Gibson and Tyndall as 15 and 19, respectively, who represent extreme departures although both have normal color vision. If one-half of a photometric field is illuminated with light of wave length 0.50μ and the other half with light of wave length 0.65μ in such amounts that the ICI standard observer would judge the two halves of the field to be equally bright, observer 15 would judge the green half to be over twice as bright as the red, and observer 19 would judge the red half to be more than 2½ times as bright as the green.

The carbon standards emit light of approximately the same quality as a hollow inclosure, or so-called "black body", at a temperature [3] of 2,100 K. Suppose we have a tungsten-filament lamp which to the ICI standard observer appears to have the same intensity as one of the carbon lamps which define the unit. The ICI observer evaluates the excess light from the carbon lamp in the red end of the spectrum as equal to the excess from the tungsten lamp in the blue end of the spectrum. It is quite obvious, however, that the tungsten lamp has a greater intensity for the observer designated by Gibson and Tyndall as no. 15, while the reverse is true for observer no. 19.

It is meaningless, therefore, to derive photometric standards for tungsten lamps from the carbon standards without specifying the observer to whom the derivation applies. Such derivations have always been made in terms of some "average observer", but confusion has sometimes resulted from a failure to indicate clearly the visibility factors actually used. The use of the same factors by everyone is of more importance than the factors themselves (within reasonable limits). Since the adoption by the International Commission on Illumination of the values recommended by Gibson and Tyndall, there no longer exists any reason for such confusion and the use of the ICI standard observer is now practically universal.

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[1] K. S. Gibson and E. P. T. Tyndall. B.S. Sci.Pap. 19,131(1923–24); S475.
[2] Recueil des Travaux, I.C.I. 16th session (Geneva), 67(1924).
[3] Those in the custody of the National Bureau of Standards have an average color temperature of 2,097 K when operating at the specified voltages.

II. METHODS AVAILABLE

In the past, 3 general methods have been used to make the step-up from carbon standards to tungsten standards. The 2 types of lamps have been compared directly by means of a Lummer-Brodhun or similar photometer, making it necessary to tolerate a large color difference in the photometric field. Under such conditions accurate measurements are out of the question and the method yields, at best, an approximate check on other methods.

The second method is to compare the 2 types of lamps by means of a flicker photometer, the criterion of brightness equality being the disappearance of flicker in the field. Some question has at various times been raised as to the theory underlying the flicker method. This method gives satisfactory precision, however, and its use is justified because it gives results in agreement with those obtained with other methods. In both of these methods, the visual characteristics of the individuals making the comparisons must be known in order to reduce the results to the basis of the average observer.

In the third method the color difference is eliminated from the photometric field by placing a blue filter in front of the carbon lamp. If the spectral distribution of the light in the 2 halves of the field is nearly the same, the characteristics of the observer's eye have a negligible effect and need not be known. The light transmission, t, of each filter i.e., the ratio of the transmitted to the incident light may be calculated from the measured spectral transmission, t_λ, the approximate color temperature θ of the incident light, and any desired set of visibility factors, V_λ, by means of the formula

$$t=\frac{\int_0^\infty \lambda^{-5}e^{-\frac{C_2}{\lambda\theta}}V_\lambda t_\lambda d\lambda}{\int_0^\infty \lambda^{-5}e^{-\frac{C_2}{\lambda\theta}}V_\lambda d\lambda} \tag{1}$$

The filter method has one decided advantage in that a particular filter may be circulated among several different laboratories to determine the differences obtained in stepping-up from one color temperature to another. If these laboratories then agree to use the same filter to set up tungsten standards and also agree to use the same value for the transmission, discrepancies in the resulting tungsten standards should not be appreciably greater than those in the carbon standards. Steps [4] have been taken to bring the tungsten standards of England, France, Germany, and the United States into agreement through the distribution of such filters. Four blue-glass filters have been circulated among the national laboratories of the countries named where their transmissions have been determined. On the basis of these determinations agreement has been reached on the transmissions to be assigned to each of the filters, one of which is retained by each of the 4 laboratories concerned. The transmissions of these 4 filters relative to each other have been very accurately determined and it is highly probable that the absolute values agreed upon apply closely to the ICI observer.

The present work was undertaken to furnish an independent check on the absolute values assigned to these filters and was completed

[4] Procès-Verbaux des Seances, Comité Int. d. Poids et Mes. 6, 324(1933).

before final agreement on these values had been reached. The results of the present work were transmitted in the form of a memorandum in July 1931 to the Advisory Committee on Electricity and Photometry of the International Committee of Weights and Measures and were later presented before the Optical Society of America at its Rochester meeting[5] on October 22, 1931. Copies of the memorandum of July 1931 were distributed to a considerable number of interested scientists. The method therein described was proposed 2 years later by Ribaud [6] who however reports no experimental work.

III. METHOD USED

Consider two black bodies, one matching in color the carbon standards and the other matching in color a tungsten lamp the candlepower of which is to be determined. The brightness of the first, B_1, may be measured by comparing it with the carbon standards as described elsewhere.[7] If now we measure the ratio of brightness of the 2 black bodies at some known wave length by means of an optical pyrometer, the brightness, B_2, of the second black body may be calculated if the temperature of one of the black bodies is known; a photometric comparison of the second black body with the tungsten lamp will then yield a value for the candlepower of the latter.

Let θ_1 and θ_2 = the respective temperatures in degrees K
B_1 and B_2 = the respective brightnesses
λ = wave length, in microns
R_0 = ratio of brightness measured at wave length λ_0
V_λ = relative visibility (for ICI observer)
C_2 = second constant in Wien's law = 14,320 micron degrees.

Then

$$\frac{1}{\theta_2}=\frac{1}{\theta_1}-\frac{\lambda_0 \log_e R_0}{14{,}320} \tag{2}$$

$$\frac{B_2}{B_1}=\frac{\int_0^\infty \lambda^{-5} e^{-\frac{14{,}320}{\lambda\theta_2}} V_\lambda d\lambda}{\int_0^\infty \lambda^{-5} e^{-\frac{14{,}320}{\lambda\theta_1}} V_\lambda d\lambda} \tag{3}$$

and

$$\frac{B_2}{B_1}=\frac{\int_0^\infty \lambda^{-5} e^{\left(\frac{\lambda_0}{\lambda}\log_e R_0-\frac{14{,}320}{\lambda\theta_1}\right)} V_\lambda d\lambda}{\int_0^\infty \lambda^{-5} e^{-\frac{14{,}320}{\lambda\theta_1}} V_\lambda d\lambda} \tag{4}$$

It is of course essential that the temperature of each black body during the photometric comparisons shall be the same as that during the optical-pyrometer determinations. This can best be assured by using black bodies immersed in freezing metals. If freezing metals are to be used, platinum is the most suitable for securing a color match with the carbon standards. The upper temperature permits of some choice. The rhodium point,[8] 2,239 K, is scarcely high enough to furnish a real test of the method. The iridium point, however, seems to be ideal. It is near the upper limit at which tungsten lamps may be

[5] J. Opt. Soc. Am. 22,7(1932).
[6] Comptes Rendus 196,687–688(1933).
[7] Wensel, Roeser, Barbrow, and Caldwell, BS J.Research 6,1103(1931); RP325.
[8] Roeser and Wensel, BS J.Research 12,518(1934); RP676.

operated without rapid deterioration. Moreover, iridium may be melted and frozen in air while rhodium must be used in vacuo. The filters which have been distributed to the national laboratories convert light of 2,100 K color temperature to light whose color temperature is about 2,400 K. To step up from the carbon standards to the iridium point, therefore, the filters must be used twice and in so doing the percentage error in the filter transmission produces twice this error in the final result. Once it has been determined that the filters can be used to make this double step without serious error, they may be depended upon for the intermediate point.

IV. FREEZING POINTS OF PLATINUM AND IRIDIUM

The freezing point of platinum [9] has been determined as 2,046.6 K (1,773.5 C) with an uncertainty not exceeding 1° K and that of iridium [10] as 2,727 K (2,453.8 C) with an uncertainty not exceeding 3° K. These determinations were each made upon the same black bodies used in the present photometric work and could be used to calculate B_2/B_1 from equation 3. These values of temperature were each obtained by measuring the ratio of brightness for red light relative to the gold point. Although uncertainties in these values do not exert their full effect in the present case because that portion of the uncertainty due to lack of purity of the metals and to temperature differences between the metal and the black body have no effect, a value of B_2/B_1 calculated by equation 3 would scarcely be accurate to 1 percent. However, in the determination of the freezing point of iridium, the ratio of brightness of the black body immersed in the freezing iridium relative to the one immersed in the freezing platinum was measured directly for wave length 0.652μ. This permits calculation by the use of equation 4 in which θ_1, the freezing temperature of the platinum need be known only approximately since a change of 100° K in θ_1 produces a change of only 1 percent in $\frac{B_2}{B_1}$. The value $\lambda_0 \log_e R_0$ was determined as 1.7480 with an uncertainty not greater than 0.0008, neglecting the 2 factors mentioned which do not affect the present work. The ratio $\frac{B_2}{B_1}$, was therefore determined with an uncertainty of somewhat less than 0.5 percent.

V. PHOTOMETRIC MEASUREMENTS

The comparison between the primary carbon standards of the National Bureau of Standards and the black body immersed in freezing platinum has been described elsewhere.[11] The comparisons between the tungsten lamps and the black body immersed in freezing iridium were made in the same manner. The high melting point of iridium required special treatment of the crucible before use as described in the paper on the freezing point.

The tungsten lamps used were six 500-watt, 110-volt, monoplane-filament projection lamps in a special T–20 bulb, with medium screw skirted base. The over-all length was 9½ in. and the distance from the

[9] Roeser, Caldwell, and Wensel, BS J.Research 6, 1119(1931);RP326.
[10] Henning and Wensel, BS J.Research 10, 809(1933); RP568.
[11] Wensel, Roeser, Barbrow, and Caldwell, BS J.Research 6, 1103(1931);RP325.

center of the filament to the tip of the globe was 5½ in. The special T–20 bulb used is 4 in. longer than that of the regular lamp, the filament being in the same position relative to the base. Life tests made on a group of the regular lamps indicated a satisfactory degree of constancy at color temperature 2,800 K, some blackening occurring at the top of the bulb. The special lamps with T–20 bulbs were then resorted to in order to remove the part of the bulb suffering the blackening from the region of the filament.

These 6 lamps, operating at a color temperature of approximately 2,727 K, were compared, both before and after the black-body comparisions, with the vacuum tungsten standards [12] which have been maintained at the National Bureau of Standards since 1911. Their average candlepower was found to be 402.4 before and 398.4 after the black-body comparisions, a change which might be attributed to an actual change in the lamps. It is unlikely, however, that such a change occurred in these lamps in the very short time that they were used during this work. They were operated at only 75 volts while their rated voltage is 110 (at which their life is 50 hours). Life tests on similar lamps indicated that no appreciable changes occur even after several hundred hours of use at 75 volts. It is perhaps unfortunate that more observations were not taken on these lamps previous to their use in the comparisons with the black body, but this fact was realized only after the values obtained at the conclusion of the work were found to be 1 percent lower. However, the uncertainty in the final result of this comparison is only slightly greater than that of the final result of the black-body comparisons. The results of the photometric observations are given in tables 1 and 2.

TABLE 1.—*Candlepower of the 6 tungsten lamps by comparison with the NBS vacuum tungsten standards of 1911*

Comparison made	Observer			
	RPT	LEB	HTW	MEL
	c	*c*	*c*	*c*
Before	402.6	399.6	404.6	402.8
After	398.5	398.3	397.1	399.5
Mean	400.5	399.0	400.8	401.2

Average for all observers 400.4±3.0 candles.

TABLE 2.—*Candlepower of the 6 tungsten lamps derived from the primary carbon standards of the NBS*

[Step-up made with black bodies immersed in freezing platinum and iridium]

Observer		
HTW	WFR	FRC
c	*c*	*c*
397.2	397.0	396.2
397.4	394.6	398.3
394.2	396.7	397.3
393.1	393.6	398.3
395.5	395.5	397.5

Average for all observers 396.2±1.7 candles.

[12] At present, unfortunately, no data are available on the question of how these standards will agree with the standards which will result from the use of the filters for which transmission values have been agreed upon.

VI. DISCUSSION

The figures ±3.0 and ±1.7 c given in tables 1 and 2 are each 5 times the probable error. This product has sometimes been called the "huge error" because it is an error such that the chance of occurrence of an equal or greater error is only one in a thousand. It is fairly certain that the accidental errors of photometric matching do not exceed these. The figure ±1.7 c, however, must be combined with the uncertainty in determining the ratio $\frac{B_2}{B_1}$ for the 2 black bodies used.

The ratio $\frac{B_2}{B_1}$, calculated for the ICI standard observer, is subject to about the same uncertainty as the measured ratio of brightness for wave length 0.652μ. This ratio was measured with a precision optical pyrometer giving complete disappearance of the filament with no color difference to bother the observer. The sector disk used had an angular opening of 25° of arc which was measured on a circular dividing engine to about 30″ of arc. The uncertainty in this measurement is, therefore, negligible. The uncertainty in the effective wave length is almost negligible, corresponding to not over 0.1 percent, while the value of C_2 used, 14,320μ deg., is estimated as uncertain by about 20, corresponding to an uncertainty of about 0.25 percent. The uncertainty in R_o, again 5 times the probable error, corresponds to 1.8 c.

The black-body comparisons are thus subject to the following uncertainties:

	c
Photometric comparisons	±1.7
Determination of R_o	1.8
λ_o	0.4
C_2	1.0
Square root of sum of squares =	±2.8

It would appear that the values derived for the NBS tungsten standards of 1911 should be lowered slightly to make them apply for the ICI standard observer. The difference, however, is just about on the border line of the experimental errors of the present work. At the time these standards were derived, the ICI observer had not yet been defined. In discussing the status of these Standards, Crittenden and Meyer [13] say "The assigned values are based on series of measurements made with the standard Lummer-Brodhun photometer by the group of observers then employed at the Bureau in photometric work" and that "the group of regular Bureau photometric observers was found to average very close to the normal observer as determined in these [14] tests." It may be considered, therefore, to a certain extent fortuitous that the 1911 derivation applies so closely to the ICI observer. In view of the excellent work which has been done on the transmission of the recently distributed filters, there is every reason to expect that the standards derived with the use of these filters will agree even more closely with the results obtained in the derivation by means of the black bodies.

[13] Proc. Int. Cong. on Ill. 1138 (1928).
[14] An average eye for heterochromatic photometry and a comparison of a flicker and an equality-of brightness photometer. Crittenden and Richtmyer, Bul.B.S., v. 14, 87(1918–1919).

VII. BRIGHTNESS OF BLACK BODIES AT OTHER TEMPERATURES

In calculating the ratio of brightness of 2 black bodies at temperatures θ_1 and θ_2, the usual formula, equation 3, page 164, is used.

The brightness of a black body at the platinum point is, without doubt, the best value to use as a base. It has been determined in 3 laboratories under conditions most favorable to high accuracy, namely upon black bodies immersed in freezing platinum. These determinations are listed in table 3.

TABLE 3.—*Brightness of a black body immersed in freezing platinum*

Date	Authority	Institution	Value reported
			C/cm²
1931	Wensel, Roeser, Barbrow, and Caldwell [1]	National Bureau of Standards	58.84
1933	Ribaud [2]	Faculté des Sciences de Strasbourg	58.78
1933	Report [3]	National Physical Laboratory	59.10
Mean value			58.91

[1] B.S.J.Research 6,1103(1931); R.P.325.
[2] Procès-Verbaux, Comité Int. d. Poids et Mes. 16,261(1933); Rev. d'Optique, 12,289(1933).
[3] Procès-Verbaux, Comité Int. d. Poids et Mes. 16,256(1933). The National Physical Laboratory Report for the Year 1933, p. 91 (issued 1934), in addition to mentioning the value 59.10 c/cm² previously reported, also reports additional observations on 60 melts and freezes yielding a value of 58.9 c/cm². This latter value is stated to be subject to revision pending further work.

The value of 58.9 c/cm² for a black body at 2,046.6 K leads to a value of 0.001602 watt per lumen for the least mechanical equivalent of light and the brightness, B, of any black body at temperature θ may be written

$$B=\frac{1}{0.001602\pi}\int_0^\infty J_\theta V_\gamma d\lambda \tag{5}$$

The relation between B and θ may be expressed by the following empirical formula which is very convenient for calculation.

$$B=2{,}495\left(\frac{\theta}{2{,}955}\right)^{\frac{461.4}{\sqrt{\theta}}} \tag{6}$$

The agreement between this empirical formula and the exact integral form, as shown in table 4, is better than one part in a thousand over the entire range from the platinum to the iridium point.

TABLE 4.—*Brightness of a black body as a function of temperature (C_2=14,320μ deg.)*

Temperature (degrees K)	Brightness		Temperature (degrees K)	Brightness	
	Equation 5	Equation 6		Equation 5	Equation 6
	C/cm²	*C/cm²*		*C/cm²*	*C/cm²*
1,550	1.273	1.297	2,200	137.0	137.0
1,600	2.077	2.107	2,239 [3]	167.1	167.1
1,650	3.295	3.330	2,250	176.1	176.1
1,700	5.091	5.130	2,300	223.9	223.9
1,750	7.679	7.720	2,350	282.0	282.0
1,800	11.33	11.37	2,400	351.7	351.7
1,828 [1]	14.02	14.06	2,450	434.9	434.9
1,850	16.38	16.42	2,500	533.3	533.3
1,900	23.24	23.27	2,550	648.8	648.8
1,950	32.41	32.42	2,600	783.7	783.6
2,000	44.46	44.47	2,650	940.1	939.8
2,046.6 [2]	58.91	58.91	2,700	1,121	1,120
2,050	60.09	60.09	2,727 [4]	1,227	1,227
2,100	80.09	80.08	2,728	1,231	1,231
2,150	105.4	105.4			

[1] Palladium point. [2] Platinum point. [3] Rhodium point. [4] Iridium point.

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