COLOR TEMPERATURE SCALES FOR TUNGSTEN AND CARBON.

By E. P. Hyde, F. E. Cady and W. E. Forsythe.

I. Introduction.

IN a paper published in 1909 by two of the present authors[1] in collaboration with Middlekauff, a new method was proposed and applied for studying the selective radiating properties of certain metals such as tungsten, tantalum and osmium as compared with a black body or with untreated carbon which approximates a black body in its radiation. This method was based on comparative measurements of the ratio of visible to total radiation for the substance to be investigated and for the black body when the two radiating bodies were heated to such arbitrary unknown temperatures that the integral color of the visible radiation was as nearly as possible the same for the two. This " color match " method was further elaborated in subsequent papers,[2] and a more rigorous definition of the " color match " criterion was given.

One of the earliest methods of estimating temperatures in industrial work was based on rough eye observations of the color of the hot body, but this has given place largely to other methods of greater precision based upon different principles. In 1907 Morris, Stroude and Ellis,[3] in a study of the relative operating temperatures of different incandescent lamps, assumed as a starting point equality of temperatures when the color of the light from the various lamps was the same, owing, as they state, to " the great divergence in the figures published by various experimenters for this quantity." In the same year Leder[4] obtained the distribution of energy in the emission of the Hefner lamp by determining the temperature of the black body when it had the same energy distribution in the visible spectrum. But in neither of these investigations was the color match method employed as a means of studying the radiating properties of metals, nor was any consideration given to the significance of the " color temperature " scale, or to its relation to true and black body " brightness temperatures " of incandescent metals.

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[1] Trans. Illum. Eng. Soc., *4*, p. 334, 1909. Presented before Am. Phys. Soc., Oct., 1908.

[2] Jour. of Frank. Inst., *169*, p. 439, and *170*, p. 26, 1910; Astrophys. Jour., *36*, p. 89, 1912.

[3] Elec., *59*, p. 584, 1907.

[4] Ann. d. Phys., Ser. 4, *24*, p. 305, 1907.

It has been customary for some years past to give a number to indicate the temperature of any radiating body by determining the temperature of the black body at which the emission intensity in some chosen wave-length is the same as that of the radiating body. This temperature is the "red" or "green" or "blue" "black-body temperature," the exact wave-length being given in accurate work. According to the method discussed in the present paper the comparison with the black body is made on the basis of the same distribution of energy in some limited region of the spectrum, usually in the visible for convenience, rather than on the basis of the same emission intensities. Hence the term "color match temperature." But since in general, precise agreement in energy distribution of the radiation from a black body and of that from one of the radiating metals studied can never be secured, the "color match temperature" has been defined more accurately as that temperature of a black body at which the relative emission intensities in some chosen two wave-lengths are the same as those of the radiating metal under investigation. Numerous experiments showed, however, that the actual match in color with a black body could be so nearly obtained for carbon, tungsten, tantalum, platinum, and osmium that the experimental errors involved in bringing these various substances to a color match by the use of an ordinary Lummer-Brodhun contrast photometer were less than the errors involved in attempting to bring the various substances to the same relative emission intensities in two wave-lengths by the use of a spectrophotometer. Consequently, after establishing this fact for the various metals to be studied the spectrophotometric method was abandoned for the more convenient method of "color match," though for accuracy of conception it must always be borne in mind that the result accomplished consists in the establishment of a condition of equal relative emission intensities in some two wave-lengths near the ends of the visible spectrum—say at 0.5μ and 0.7μ.

As a consequence of the results obtained with this method, and from other knowledge of the radiating properties of these metals it was concluded that quite probably the "black body color temperature" of any of these metals would be higher than the true temperature. If this be true then the color temperature and the "black body temperature" obtained in the customary way, and which we shall hereafter designate[1]

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[1] The "color match temperature" is also a black body temperature and so it becomes necessary to designate more precisely the so-called "black body temperature" defined in the customary way. It is proposed, therefore, to designate the latter as "black body brightness temperature," or more briefly, "brightness temperature," giving the wave-length where necessary, and to designate the former as "black body color temperature," or more briefly, "color temperature," giving the two wave-lengths in cases where an integral color match cannot be obtained, or is theoretically insufficient.

the "black body brightness temperature," or, for the sake of brevity, "brightness temperature" would give two limits between which the true temperature would lie, and since the latter is so difficult of measurement, the ascertainment of the upper and lower limits would give valuable information. Moreover the simplicity of the process of determining the color temperature suggested the advisability of using this method to give a number to the temperature of radiating metals instead of the older and more commonly used method of determining the brightness temperature which involves more elaborate apparatus, and, in the case of filaments of small diameter, is subject to possible large errors. If suitable apparatus is available, and proper precautions are taken, the brightness temperature may be obtained with greater accuracy.

In the present experiments the color temperatures of tungsten and carbon are determined, and comparison is made between color temperature, brightness temperature and true temperature of tungsten, using Worthing's[1] data for the latter, and between color temperature and brightness temperature of carbon. The relation is also determined between color temperature and lamp efficiency in lumens per watt, so that it may be possible to locate the color temperature and also the true temperature from measurements of lamp efficiency.

In the earlier papers by two of the authors, to which reference already has been made, the color temperature of tungsten at low voltage was measured directly against a black body, and color temperatures at higher voltages were determined by spectrophotometric comparisons. Moreover comparative data were presented on the brightness temperatures from observations by Waidner and Burgess, but, as will be pointed out later, these early values were only approximate as the emphasis at that time was placed on the application of the "color match" method in the study of selective radiation. In 1915, Shackelford,[2] working in this laboratory, showed that the color of the radiation from the inside of a helical tungsten filament was not so white as that of the radiation from the exterior of the helix, even though the temperature inside was at least as great as that outside. Subsequently Langmuir[3] published the same observation and employed the observed data to given an approximate scale of color temperatures.

Paterson and Dudding[4] in a recent investigation *assumed* that the color temperatures are approximately the same as the true temperatures and obtained results which seemed to show that this assumption was not

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[1] Jour. of Frank. Inst., *181*, p. 417, 1916; Phys. Rev., Ser. II.

[2] Jour. of Frank. Inst., *180*, p. 619, 1915; Phys. Rev., Ser. II., *8*, p. 470, 1916.

[3] Phys. Rev., Ser. II., *7*, p. 302, 1916.

[4] Proc. of Phys. Soc. (Lond.), *27*, p. 230, 1915.

greatly in error, as they were not attempting to work to an accuracy greater than 1 per cent. in temperature.

II. Apparatus and Method.

An outline of the arrangement of the apparatus used to make the measurements is shown in Fig. 1. The furnace shown diagrammatically in Fig. 2 was a vacuum carbon tube furnace somewhat similar to one already described.[1] This furnace, with different graphite tubes, was used in most of the experiments, although some check measurements at low temperatures were made, with platinum-wound porcelain and alundum tube black-body furnaces of the Lummer-Kurlbaum type. The carbon furnace shown in the figure was operated from a transformer supplied with 440 volts which was stepped down to 40 volts. With this source of supply there were required from 50 to 100 amperes through the primary to heat the furnace to temperatures ranging from 1600° K. to 2600° K. The current through the primary could readily be varied in small steps and so the current through the heater tube, and consequently the temperature of the heater tube, were easily controlled.

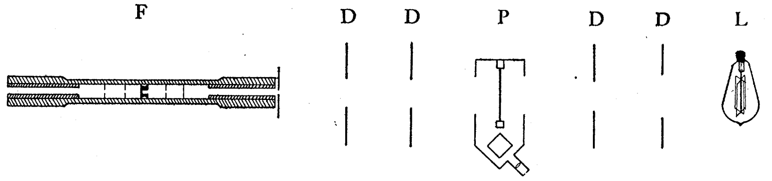

Fig. 1.
Arrangement of apparatus.

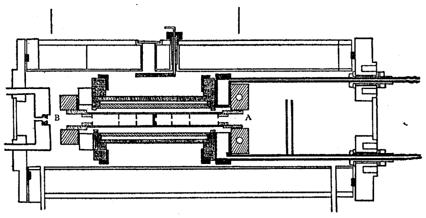

Fig. 2.
Diagrammatic sketch of furnace. A. Heater tube. B. Limiting diaphragm.

Diaphragms, as shown, were very carefully located so that no light reached the photometer except from the central diaphragm. This central diaphragm was made as thin as possible, being only a fraction of a millimeter thick at the central part. All diaphragms were so cut along the outer edge that they touched the heater tube only along two V-shaped edges.

The furnace was so mounted that observations could be made through

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[1] Astrophys. Jour. *34*, p. 353, 1911.

the diaphragm at either end. Inasmuch as the heater tube was mounted symmetrically inside the container, and the diaphragms inside the heater tube were equally spaced on each side of the central one, there was no reason to expect differences in temperature or blackness between the two ends.

The temperature of the central diaphragm was measured by means of a laboratory form of the Holborn-Kurlbaum optical pyrometer, directed toward one end of the furnace while a color match was being determined for the light coming through the other end. Thus changes in the temperature due to slight changes in the heating current could be detected and corrected for. In order to be sure that the temperatures at the two sides of the diaphragm were the same, measurements were made on the temperature at each side with different optical pyrometers, before and after each set of measurements on the color. In no case was a larger difference found than 2° or 3° C. The pyrometers were calibrated, using a platinum-wound black-body furnace held at the temperature of melting palladium taken at 1828° K. Extrapolations for the higher temperatures were made by means of Wien's equation using sectored disks. Two thicknesses of red glass (6.8 mm.) (Rotfilter No. F 4512) were used before the eyepiece of the pyrometer. The effective wave-lengths of the red glass were obtained in a previous investigation.[1] The temperature scale[2] used was based on the following values:

Melting point of gold = 1336° K.,

Melting point of palladium = 1828° K.,

$C_2 = 14{,}350\mu \times \text{deg}.$

In making the color temperature determinations the integral light from the furnace was matched in color with that from a comparison lamp using a Lummer-Brodhun contrast photometer and the black body color temperature was transferred to the test lamps by the substitution method.

In making a set of measurements a reading was first taken in the neighborhood of 1800° K., then at higher points and at the end again in the neighborhood of 1800° K. If the first and last readings were in good agreement it was assumed that working conditions were satisfactory. In the early part of this work the only diaphragms in the heater tube were central diaphragms and the diaphragms near the end. While no very great differences were obtained when the heater tube was used as shown, greater weight is given to the later results.

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[1] Astrophys. Jour., *42*, p. 294, 1915.

[2] The reasons for the adoption of this temperature scale will be published in the October number of the General Electric Review.

The brightness temperatures of the lamps were determined directly with the same optical pyrometer using a very large magnification. This temperature for the tungsten lamp was also measured by color matching the lamps under investigation with a tungsten lamp having a large filament (0.25 mm. diam.), then measuring the brightness temperature of the large filament. The values obtained by the two methods checked very well but the latter gave the least variations in the result. The values found for the brightness temperature of the tungsten filament as a function of the mean horizontal candles per watt, check well within the limit of error with results on the same relation obtained previously.[1] The values for carbon do not show as good an agreement, due no doubt to the fact that in the previous case treated carbon filaments were used, while in this work untreated filaments were used. It was not possible to get untreated carbon lamps with sufficiently uniform filaments. Consequently the brightness temperatures of the carbon filaments were measured in several places and the mean taken.

The comparison lamp for most of the measurements, and three of the test lamps were 40-watt, 110-volt, drawn-wire, vacuum tungsten lamps. These lamps had their lower supports welded and at the upper supports the filament was held taut by a coiled spring. The other test lamp was a 100-watt, 120-volt tungsten lamp of the old type having welded lower supports, and is the same lamp used in previous investigations.[2] In some check measurements a 25-watt tungsten lamp of the same type as the 40-watt lamp was used, and a 30-watt, 110-volt anchored-oval carbon filament lamp was used as a comparison lamp. In determining the brightness temperatures a single-loop vacuum tungsten lamp was used, made with a filament of 10 mil (0.254 mm. diameter) wire and about 30 cm. long in a bulb approximately 5 inches (12.7 cm.) in diameter.

III. CORRECTION DETERMINATIONS.

The glass serving as the window of the furnace was not entirely nonselective in its transmission, thus introducing a possible source of error. As at all times the substitution method was employed the error was practically avoided by inserting the same glass between the photometer and the test lamp when transferring from the comparison lamp to the test lamp. Hence this source of error was not directly determined and is not included in the applied corrections (see Table I.).

The selective absorption of the lamp bulbs was corrected by measure-

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[1] PHYS. REV., *34*, p. 333, 1912. (Correction must be made to the temperature scale used in the present investigation.)

[2] Jour. of Frank. Inst., *169*, p. 439, 1910.

Table I.

Relation between Lumens per Watt and Color Temperature for a Tungsten Lamp.

Lumens per Watt (Uncorrected).	Color Temperature (Uncorrected).	Lumens per Watt (Corrected).	Color Temperature (Corrected).
0.5	1644	0.58	1663
1.0	1777	1.14	1794
1.5	1866	1.70	1883
2.0	1939	2.26	1955
2.5	1998	2.82	2014
3.0	2050	3.37	2066
3.5	2096	3.93	2112
4.0	2138	4.48	2153
4.5	2175	5.02	2190
5.0	2208	5.57	2224
5.5	2241	6.12	2257
6.0	2269	6.66	2285
6.5	2299	7.21	2315
7.0	2327	7.76	2343
7.5	2354	8.30	2370
8.0	2380	8.85	2397
8.5	2406	9.39	2423
9.0	2431	9.94	2449

ments of the transmission for different wave-lengths with a spectrophotometer. This correction expressed in terms of the change in color temperature amounted to about 6° at 1800° K. The lumens per watt of the lamps were corrected for the cooling effect of the leading-in and supporting wires.[1] A correction to the measured lumens was made also for the absorption of the lamp bulbs. These corrections may be evaluated from the data on uncorrected and corrected color temperature and lumens per watt as given in Table I. (which see).

IV. Experimental Results.

(*a*) *Color Temperature versus Lumens per Watt.*—In order to show the agreement among the various observations all of the observed points are plotted in Fig. 3, in which the coördinates are color temperature and voltage of $T-1$, a 120-volt, 100-watt tungsten vacuum lamp which has been used in previous experiments involving color temperature. It is seen that for the most part the points lie within 5° of the curve, the worst deviation being 16°.

Before presenting the experimental results obtained on the relations between the color temperature, the brightness temperature and the true temperature of tungsten, it seems best to give the observed relation between the color temperature of tungsten and the lamp efficiency,

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[1] Trans. Illum. Eng. Soc. (U. S.), *6*, p. 238, 1911.

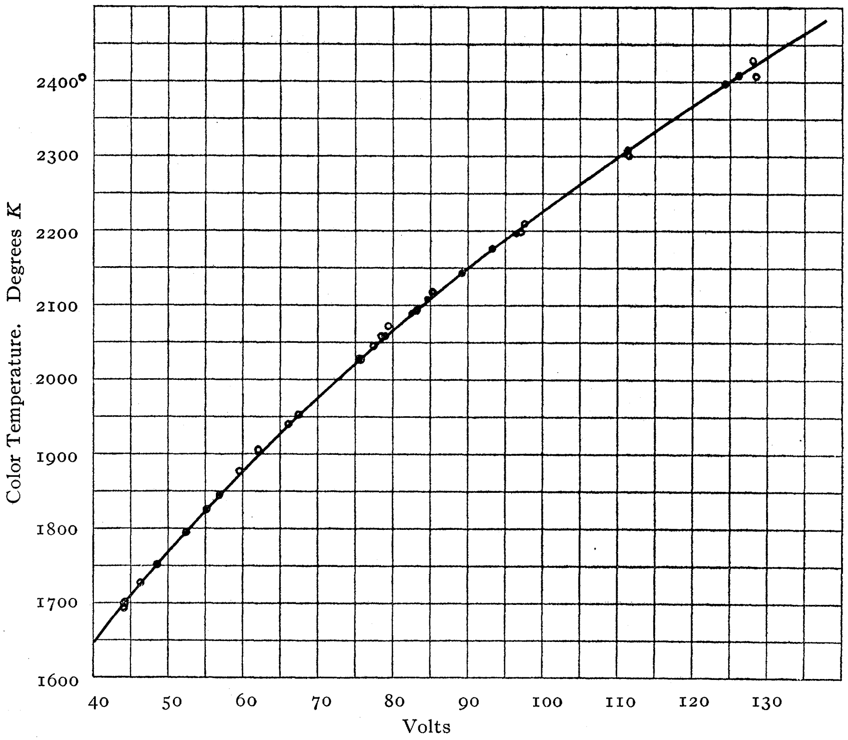

Fig. 3.

The relation between color temperature and volts of a certain tungsten lamp, showing agreement of observed data.

expressed in lumens per watt. The results are shown in Table I. and Fig. 4. This relation is independent of the size and shape of the filament, provided it is operated in a vacuum. The lumens per watt of a lamp are relatively easily determined with a moderately high accuracy, and so by establishing the relation between the lumens per watt and the color temperature the latter may readily be found for any tungsten lamp if the various corrections for bulb absorption and conduction losses are known. Since these latter, though of the same magnitude for different lamps of the same general type, are still somewhat different for different bulbs and for filaments of different size, the results are given in the original uncorrected values, and also corrected for all these sources of error. Any investigator may determine the magnitude of these correction factors for any lamp he may study, or, if so great an accuracy is not required, he may assume that the corrections are sensibly the same for his lamps as for those used in the present investigation, and he may therefore use the uncorrected values.

In the experiments described, four tungsten lamps were carefully color-matched with each other at various points throughout the range. It was found that a definite change in color temperature corresponded to the same relative change in voltage for each lamp within the errors of observation. Measurements of the mean horizontal candle-power were then made with the lamps operating at voltages to give the same color as that of the carbon standards in terms of which they were being measured. In order to avoid the difficulties due to heterochromatic photometry it was decided to determine the candle-power at other voltages by using the table published by Middlekauff and Skogland.[1]

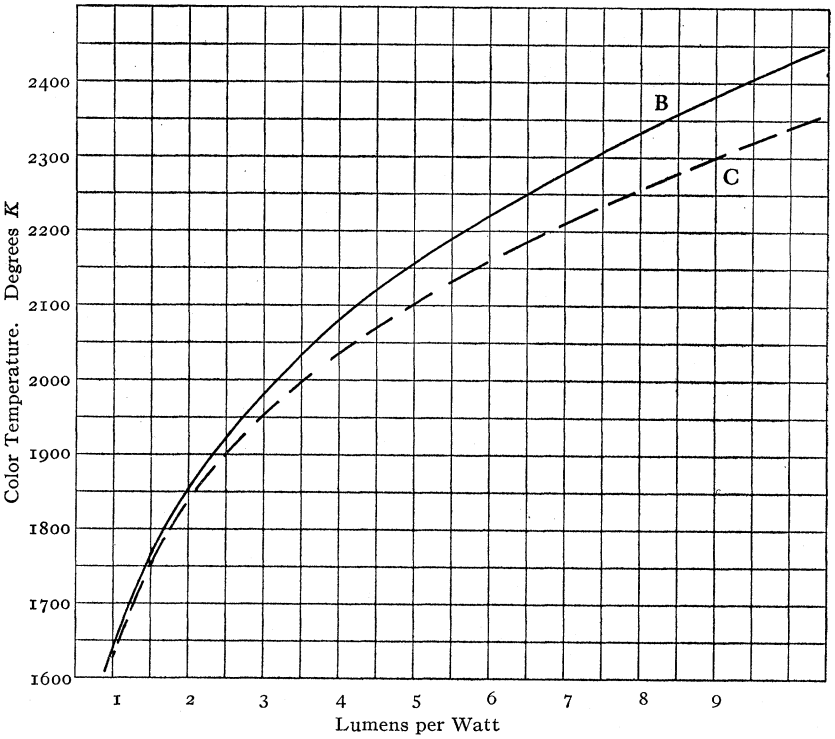

Fig. 4.

The relation between color temperature and lamp efficiency of tungsten. *B*. Author's data. *C*. Paterson and Dudding's data.

In Fig. 4, for comparison, the corresponding uncorrected curve for tungsten obtained by Patterson and Dudding is drawn as a dashed line. In the neighborhood of 1600°–1700° K. the two curves are in as close agreement as could be expected in view of the disclaimer of Paterson

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[1] Bull. Bureau of Standards, *11*, p. 483, 1915.

and Dudding of an accuracy better than about 20°, but at the higher temperatures the differences between the two curves are much too large to be accounted for on this basis, as at 2400° K. the difference amounts to approximately 85°. In the neighborhood of 2023° K. (1750° C.) the difference is 30°–40° and if this correction were assumed in determining from Paterson and Dudding's data the color temperature of platinum at its melting point, using the tungsten comparison lamp, the melting point would have a color temperature of about 2080° K. (1807° C.) or some 50°–60° above the true temperature, which difference would show beyond question that the color temperature of melting platinum is definitely higher than the true temperature, a result which must follow from other published data on platinum. It may be stated in passing that no attempt will be made to justify the discrepancy between the value found by Paterson and Dudding using a tungsten comparison lamp, and that derived from a similar comparison against a carbon lamp. They should, of course, be the same, but it should be stated once more that these authors do not claim any greater accuracy than that indicated by the difference in results in these measurements.

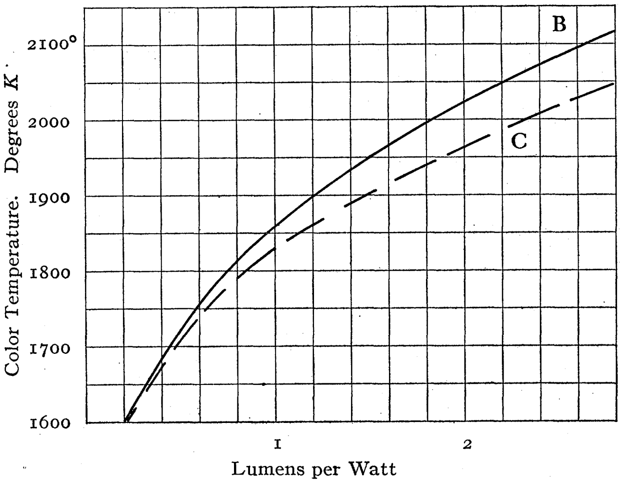

Fig. 5.

The relation between color temperature and lamp efficiency of carbon. *B*. Author's data. *C*. Paterson and Dudding's data.

The data on the relation between color temperature and lumens per watt for untreated carbon are given in their observed, or uncorrected form, in Fig. 5. The corresponding curve obtained by Paterson and Dudding is also given for comparison, but it should be noted that the latter curve is based on measurements on both treated and untreated carbon filaments, whereas the authors' data are entirely confined to untreated carbon. Owing to the irregularities in the untreated carbon filaments the accuracy attainable is not nearly so great as that possible with tungsten, and this fact, together with the consideration of the relatively smaller errors introduced by end conduction losses, has suggested the inadvisability of attempting to give a corrected curve, as was done for tungsten.

(*b*) *Color Temperature, Brightness Temperature and True Temperature.* —Reference has already been made to the fact that two of the present authors[1] together with Middlekauff some years ago published results on the color and brightness temperatures of various metals, giving also the lumens per watt, but those results will be found somewhat different from the present values owing to several reasons, principally the lack of knowledge at that time of various correction factors to be applied. Thus the values of color temperature given were for the most part determined from energy-distribution curves obtained by means of the spectrophotometer, and the slit-width corrections in spectrophotometric measurements had not then been investigated.[2] Moreover the brightness temperatures given in the earlier publication were intended only as approximate values, as was stated in the paper.

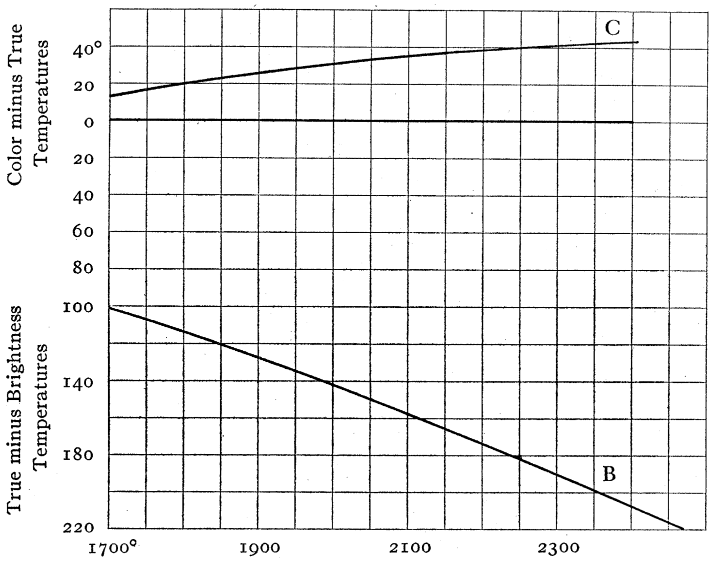

Fig. 6.

The relation between color, true, and brightness temperatures of tungsten.

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[1] See references 1 and 2, p. 395.

Astrophys. Jour., 35, p. 237, 1912.

The results obtained in the present investigation are shown in Figs. 6 and 7. In Fig. 6 the differences between the true temperatures[1] and the color and brightness temperatures for tungsten are given, the color temperature values being corrected for the various errors enumerated in an earlier section. The observations bore out the expectation that the color temperature would be larger than the true temperature for all temperatures, whereas the brightness temperatures are of course considerably smaller. The brightness and color temperatures are seen to give upper and lower limits to the true temperature, with the difference from the true temperature considerably less in the case of the color temperature. This general result would very probably be found to obtain for a number of metals, since available data on the reflecting powers and also other indications of the optical properties of many metals show quite general selective absorption of the shorter wave-lengths.

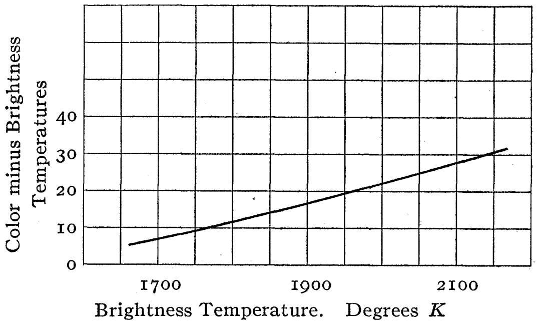

Fig. 7.

The relation between color and brightness temperatures of carbon.

It should be noted that the difference curve between color temperature and true temperature, if prolonged toward lower temperatures, would apparently cross the axis, indicating that the color temperature would be lower than the true temperature if the comparison were made at sufficiently low temperatures. There is no physical reason to believe this to be true. It is far more probable that the shape of the difference curve is subject to modification. In the first place it must be emphasized that experimental errors may occur as large as 5° and possibly somewhat larger. In the second place differences in the emissivities of different samples of tungsten may modify this difference curve slightly, since the true temperature and the color temperature are obtained independently from the brightness temperature, using different lamps.

Direct measurements of the relative intensity of emission in the red

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[1] Jour. of Frank. Inst., *181*, p. 417, 1916; PHYS. REV., Ser. II.

and in the blue, with an optical pyrometer, calibrated in brightness at the two wave-lengths by comparison with a black body, give a color temperature curve which differs slightly from the color temperature curve obtained by integral color match, and indicate a difference curve between the color temperature and the true temperature more nearly of the form one might expect. But since the difference between the curves is quite probably within the experimental accuracy, and since, moreover, there is always the possibility that with so selective a radiating body as tungsten the integral color temperature may differ slightly over a wide range of temperature from the color temperature determined from any two chosen wave-lengths (approximately 0.665μ and 0.467μ in these experiments), it has seemed advisable to adhere to the observed curve as given in Fig. 6, since this is the curve of more practical value.

Independent measurements with a spectrophotometer, and computations from observed data on the brightness of a black body (to be published shortly) both give color temperature scales in substantial agreement with the observed scale (Fig. 6).

The results for carbon are given in Fig. 7. As stated previously the data on carbon do not justify any attempt to apply corrections similar to those determined for tungsten. In the case of carbon, since there are no reliable data on the true temperature, the differences between the brightness temperatures and the color temperatures only are plotted.

(*c*) *Relation between Color Temperature and Watts.*—Various attempts have been made to determine the exponent β in the assumed generalized form of the Stefan-Boltzmann law for metals,

$$E = \sigma T^{\beta}.$$

It is of interest to inquire into the possible existence of a similar relationship between the total radiation and the color temperature. If the color temperature of a lamp is known at some one wattage and if a simple law is found to hold for the relationship between color temperature and wattage, the application of this law affords a convenient way to establish the entire color temperature scale. The investigation of this relationship is interesting also because its consideration in conjunction with that of other established relationships furnishes a check of the original observed color temperature scale.

Paterson and Dudding give for the above relationship for carbon lamps (including both untreated and flashed filaments)

$$W \alpha T^{4.58},$$

and for tungsten lamps

$$W \alpha T^{5.1},$$

indicating a constant exponent for both metals.

Measurements by the present authors, of watts *vs.* color temperature (uncorrected) for tungsten and carbon, with the corresponding computed values of the exponent β at different regions of the total temperature interval investigated are given in Tables II. and III.

Considering the data for tungsten (Table II.) it is seen that there is a

TABLE II.

Relation between Color Temperature and Relative Watts for a Tungsten Lamp Including Corresponding Values of β.

Color Temperature (Uncorrected).	Relative Watts.[1]	β Computed from Data on Color Temperature and Watts.	β Computed from Other Data.
1750	22.3	4.99	4.93
1800	25.7	4.98	4.90
1850	29.3	4.79	4.87
1900	33.4	4.89	4.84
1950	37.8	4.80	4.81
2000	42.6	4.77	4.79
2050	47.9	4.68	4.76
2100	53.6	4.69	4.74
2150	60.0	4.82	4.72
2200	66.9	4.73	4.70
2250	74.5	4.79	4.68
2300	82.6	4.72	4.67
2350	91.5	4.71	4.65
2400	100.9	4.66	4.64
2450	110.2	4.26	4.62
Average.		4.75	4.75

[1] 100 = watts corresponding to 1.2 watts per mean horizontal candle.

TABLE III.

Relation between Color Temperature and Relative Watts for an Untreated Carbon Lamp Including Values of β.

Color Temperature (Uncorrected).	Relative Watts.[1]	β.
1650	38.9	——
1700	43.8	4.03
1750	49.2	4.01
1800	55.1	4.06
1850	61.5	3.95
1900	68.4	3.97
1950	76.0	4.11
2000	84.2	4.00
2050	92.9	3.97
2100	102.4	4.09
Average.		4.02

[1] 100 = watts corresponding to 4 watts per mean horizontal candle.

distinct indication of a gradual decrease in β as the temperature increases, although the successive values of β are not always consistent. This inconsistency is due to slight irregularities in the observed color temperature scale. The average value of β over the observed range of temperature is 4.75, differing from the value of Paterson and Dudding in the direction to be expected in view of the difference between the two temperature scales. The following considerations show, however, that the observed indication of a decreasing β with increasing temperature is verified in fact.

If I represents candle-power, and if T_1 and T_2 are two color temperatures at any region of the interval but differing from each other by an infinitesimal amount, then the following relations hold:

$$\frac{I_2}{I_1} = \left(\frac{T_2}{T_1}\right)^l, \tag{1}$$

$$\frac{W_2}{W_1} = \left(\frac{T_2}{T_1}\right)^\beta, \tag{2}$$

$$\frac{I_2}{I_1} = \left(\frac{W_2}{W_1}\right)^{k'} = \left(\frac{T_2}{T_1}\right)^{\beta k'}. \tag{3}$$

From equations (1) and (3)

$$l = \beta k'.$$

If the subscript " 0 " is used to refer to a black body at the same color temperature, then

$$\frac{l}{l_0} = \frac{\beta k'}{\beta_0 k_0'},$$

and hence, since $\beta_0 = 4$,

$$\beta = 4 \frac{l}{l_0} \frac{k_0'}{k'}. \tag{4}$$

Now k', which is the percentage change in candle-power for one per cent. change in watts is accurately known for tungsten lamps, uncorrected for end effects, and the corresponding quantity k_0' for a black body is known by computation[1] to within a very small uncertainty. There is, of course, the error in locating the precise color temperature of tungsten,—the very error which gives rise to the present uncertainty as to the constancy of β for tungsten, but the observed color temperature scale is certainly correct to within an error of the order of magnitude of 10° and an error of this magnitude would affect k' by only 0.6 per cent. to 0.7 per cent., whereas the ratio k_0'/k' varies by 5 per cent. over the temperature interval 1700° to 2150° K.

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[1] Astrophys. Jour., *36*, p. 89, 1912.

If now l/l_0 can be determined, substitution in equation (4) will give values of β for tungsten. " l " is the exponent giving the relative change of candle-power of tungsten for a small change in color temperature, and " l_0 " is the corresponding exponent for a black body. In a previous paper[1] by one of the authors a criterion (Criterion I.) was established for determining the constancy in emissivity of metals in the visible spectrum, and it was shown that if the emissivity in the visible is constant for some metal over a given interval of color temperature, then the relative candle-power of the metal and the black body over that interval of color temperature will be the same, and so for small steps in that interval $l/l_0 = 1$.

Although this criterion was apparently fulfilled for carbon and tantalum, there was found a slight deviation in the case of tungsten, which since that time has been verified and more accurately evaluated.[2] The deviation in the case of tungsten is approximately 1.5 per cent. and sensibly the same over the temperature interval investigated. Putting for l/l_0 its value 0.985 and for k_0'/k' the values obtained as indicated, the values of β may be computed to a fairly high accuracy. Values obtained in this way are given in the fourth column of Table II. The agreement between these values of β and the observed values, given in the third column, is as good as might be expected, and if, reversing the process, a color temperature scale should be constructed from the computed β's it would agree with the observed scale within less than 5°, which is within the experimental error. The average values of β by the two methods are in excellent agreement.

The values of β for untreated carbon are given in Table III. It is probable that β is very nearly, if not quite constant for carbon over the observed temperature interval, and the uncertainty in the observations, owing to the lack of uniformity in the untreated carbon filaments vitiates any effort to analyze the results further. As in the case of tungsten, the average value of β for carbon is less than the value found by Paterson and Dudding, but here again this is to be expected in view of the difference in the corresponding color temperature scales.

SUMMARY.

The " black body color temperatures " or simply the " color temperatures " for tungsten and untreated carbon lamps are given from direct observations against a carbon-tube black-body furnace, plotted against lumens per watt of the lamp.

For tungsten the differences between the " color temperature," the

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[1] Loc. cit.

[2] Worthing, loc. cit.

" brightness temperature " (ordinarily called heretofore the " black-body temperature "), and the true temperature are given, and it is pointed out that the color temperature is greater than the true temperature, whereas the brightness temperature, as is well known, is less than the true temperature. The color temperature, however, is much nearer the true temperature.

For carbon the difference between the color temperature and the brightness temperature is given, the true temperature being unknown.

The relation between the color temperature and the watts is investigated, and found, within observational errors to obey approximately an exponential function. It is shown that for tungsten the exponent cannot be a constant, but must decrease slightly from to low high temperatures.