THE TRUE TEMPERATURE SCALE OF TUNGSTEN AND ITS EMISSIVE POWERS AT INCANDESCENT TEMPERATURES.

By A. G. Worthing.

Introduction.

A TRUE temperature scale for tungsten at incandescent temperatures based on sound principles was first obtained by Pirani[1] when he bent a tungsten ribbon back and forth so as to obtain a cavity largely surrounded by it, which was raised to incandescence in the ordinary manner by a heating current. He concluded that the radiation coming from the interior of the cavity was black body radiation. Thus he was able to express, with the aid of a Holborn-Kurlbaum optical pyrometer, the relation between the brightness temperature[2] of the natural tungsten radiation and the true temperature of the tungsten, that is the brightness temperature of the radiation from the cavity. An emissive power relation follows simply. He concluded that for $\lambda = 0.64\mu$ the emissive power was constant and equal to about 0.485. However the uncertainty as to this result was rather large, being stated as $7\frac{1}{2}$ per cent.

Soon afterwards Mendenhall and Forsythe[3] used a narrow V-shaped trough and in a similar manner obtained a temperature scale which involved emissive powers increasing with temperature from 0.45 at 1100° C. to 0.66 at 2900° C. Unfortunately their results were subject to considerable error because the two strips separated at the apex of the V at high temperatures.

Two other scales based on somewhat similar pyrometer measurements have been developed by Pirani and Meyer[4] and by Langmuir.[5] In both instances the brightness of the interior of a closely wound tungsten helix was compared with the brightness of the exterior. Pirani and Meyer's results indicate that the emissive power at the wave-length 0.532μ, which

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[1] Phys. Zeit., 13, p. 753, 1912.

[2] Heretofore the term "black body temperature" has been used to designate this quantity. The reasons for abandoning this term in favor of "brightness temperature" are fully stated by Hyde, Cady and Forsythe in the paper following this.

[3] Astrophys. Jour., 37, p. 380, 1913.

[4] Elektrot. u. Masch., 33, pp. 397 and 414, 1915.

[5] Phys. Rev., II., 6, p. 138, 1915.

seems to have been used by them, is constant with temperature and equal to 0.44. Langmuir concluded that the emissive powers at 0.667μ and 0.537μ were independent of the temperature and equal respectively to 0.465 and 0.485. Later[1] he concluded 0.46 to be the most probable value for the wave-length 0.664μ. The difference between the two scales for 0.532μ and 0.537μ is considerable. The earlier temperature scales which these experimenters had arrived at, and to some extent, the later scales just reported, have been founded on or tempered by the results of Holborn and Henning[2] who concluded that the emissive powers of silver, gold, platinum, and palladium in the visible spectrum were independent of the temperature.

Shackelford[3] working in this laboratory, using helical coils of varying pitch, and extrapolating for the case of a closed helix obtained, for a red brightness temperature of 2300° K. (true temperature of 2530° K.), 0.445 as the emissive power at 0.656μ and 0.465 at 0.493μ. At a temperature about 400° lower values slightly larger were obtained. Others have measured the emissive power of tungsten at some one temperature. These are well summarized by Burgess and Waltenberg[4] who obtained 0.39 at 2020° K. for 0.65μ. Considering further only the later values as the more probable, there are in addition Coblentz's[5] 0.474 at 0.65μ, Wartenburg's[6] 0.51 at 0.65μ and Littleton's[7] 0.545 at 0.589μ, all of which refer to room temperature. Other temperature scales depending on the fact that the luminous flux from a tungsten filament may be matched in color with that from a black body are discussed in the following paper by Hyde, Cady and Forsythe.

METHOD AND APPARATUS.

General Procedure.—In the present work, except for the measurements at room temperature, as will appear later, long tubular filament of tungsten with small holes penetrating the side walls at various places have been made use of. In general terms, the procedure has consisted of determining with an optical pyrometer the ratio of the brightness of the filament surface adjacent to a hole, in a region suitably chosen from the standpoint of constancy of temperature, to the brightness of the hole, when the filament was heated to incandescence in a vacuum or in an

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[1] PHYS. REV., II., 7, p. 302, 1916.

[2] Berl. Ber., p. 311, 1905.

[3] Jour. Frank. Inst., 180, p. 619, 1915, and PHYS. REV., II., 8, p. 470, 1916.

[4] Bull. Bur. of Stds., 11, p. 591, 1915.

[5] Bull. Bur. of Stds., 7, p. 197, 1911.

[6] Verh. der Deut. Phys. Gesell., 12, p. 105, 1910.

[7] PHYS. REV., 35, p. 306, 1912.

atmosphere chemically inert. On the assumption that the radiation from the hole is black and that there is a negligibly small difference of temperature between the interior and the surface, such a ratio represents an emissive power for a wave-length depending on the light transmitted by the pyrometer glass screen, and for a temperature corresponding to that of the radiation from the hole. This latter temperature was obtained in the standard manner with the aid of Wien's law by comparing the black radiation with that from a calibrated black body of the ordinary type at the palladium point. As already noted a brightness temperature true temperature relation follows simply. The assumptions made and the corrections for the lack of their fulfillment are considered in detail in the section on Corrections and Errors.

Preparation of Filaments.—The filaments themselves were formed according to the commercial method common about five years ago by squirting a paste of tungsten powder held together by a binder through a die, in the present case one with an annular opening. Shortly after the actual squirting, when the tubes were of the proper consistency, small holes were pierced in many places through the walls. Following the usual drying and heating, the filaments were mounted in lamp bulbs. At this stage the filaments used had external and internal diameters of about 1.3 mm. and 0.8 mm. respectively. The holes through the walls were nearly circular and of two sizes, approximately 0.09 mm. and 0.12 mm. in diameter.

Much difficulty has been experienced in mounting these filaments in lamp bulbs because of the extremely large currents, 100 amperes being the maximum, which were required. It was considered impracticable, after several failures, to use soft glass bulbs. Many successful lamps using hard glass have been made, but the bulbs of those made at first contained so many bad streaks that it was often impossible even with selected bulbs, to obtain observations on more than one or two portions of the filaments. The later lamps have been fairly satisfactory in this respect, however. Some of the bulbs have been evacuated, but most of the data reported have been on filaments immersed in a gas, usually argon.

Apparatus.—The optical pyrometer used was of the Holborn-Kurlbaum or Morse type such as has been used quite commonly in this laboratory.[1] As pyrometer screens a red glass, Jena F–4512, and a blue uviol glass in single and double thicknesses have been used. As will be shown later, the changes in thickness and the lack of monochromatism were readily corrected for, so that the final results may be considered as applying

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[1] Phys. Rev., II, 4, p. 163, 1914.

strictly to two definite wave-lengths, viz., 0.665μ and 0.467μ. Photographs are reproduced in Fig. 1, which show considerably magnified what is seen when the pyrometer filament appears somewhat less bright than the hole but brighter than the adjacent surface for each of the two sizes of holes used.

PRELIMINARY TESTS.

As is usually the case, these tests are preliminary from the standpoint of character rather than from the standpoint of time of performance. They represent tests which were essential, before any reliability could be placed upon the main experimental data obtained.

Uncertainty Due to Smallness of Holes.—Fig. 1 suggests that, due to the smallness of the holes, from physiological and psychological grounds, one might be expected to make erroneous judgments, thus vitiating the results. In order to test this, pyrometer settings were made on an extended luminous background such as was described by Lorenz,[1] first when viewed through a fine needle hole in an opaque screen just in front of the background, then when viewed without the opaque screen. With the fine needle hole of approximately the same size as the holes in the filaments used, no systematic differences in the pyrometer readings, which depended upon the presence or absence of the opaque screens, were noticeable. The same conclusion as to freedom from error on this account was borne out by the results obtained with changes in the magnification under workable conditions.

Distortion in Temperature Distribution Due to Presence of Holes.—Unquestionably the presence of such holes as were pierced in the walls of the filament caused variations in the temperature distribution in their neighborhood. Many times tests for such changes including settings as close as 0.02 mm. to the edge of the hole were made, but in no case was such an effect detectable.

Constancy of Temperature of the Surface on a Given Circumference.—Broken filaments showed in general that the inner and the outer surfaces of the filament wall were not coaxial, but that the maximum and minimum thicknesses of wall at any one cross-section varied as much as 7 to 5. Attempts to determine the effect of this mathematically have been unsuccessful. Pyrometer settings at various positions around a circumference revealed no certain differences at temperatures above 1500° K. Data at lower temperatures were not conclusive. It is further believed that in the average any effect of this type would be eliminated.

Effects of Preliminary Heating.—The first results obtained showed that

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[1] Elec. World, 61, p. 932, 1913.

Physical Review, Vol. X., Second Series,
October, 1917.

Plate I.
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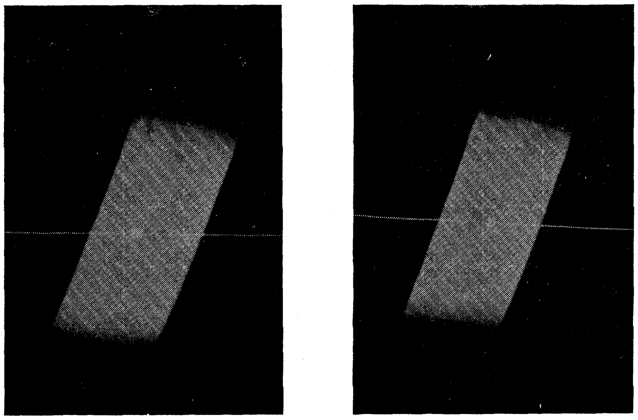

Fig. 1.

Photographs showing the pyrometer filament projected against the hole and the surface as a background for each of the two sizes of holes used.

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a gradual change was taking place. With continued operation the values obtained for the emissive powers gradually decreased, the total change amounting to as much as 7 or 8 per cent. of the quantity measured. It was soon found that the filament could quickly be brought fairly close to its final steady state by a preliminary heating for a short time at a high temperature. In subsequent work such preliminary heat treatment at about 2800° K. was always given, usually previous to the completion of the lamp, while it was still connected with the evacuating pump. That such a temperature was reached was assured by a method common in this laboratory, in which there were compared the colors of the two shadows of a pencil or some slender opaque object on a piece of white paper as produced by the lamp being tested and an ordinary commercial 100-watt gas-filled tungsten lamp. It is necessary to have the two shadows about equally bright. In the heat treatment given, the temperatures reached were always such as to indicate that the color of the light from the lamp tested was noticeably bluer than that from the commercial lamp.

Effects of Lack of Surface Polish.—The accidental short-circuiting of a resistance, which caused the filament being studied to melt at a certain cross-section, was apparently also the means whereby the surface was partially polished. The subsequent tests with this filament seemed to give lower values for the emissive power than were obtained previously. Later tests on polished and ordinary unpolished filaments showed this effect to be real and to account for differences which may amount to two per cent. in the emissive power. By variations in the process of preparing squirted tungsten filaments, filaments having various surface appearances may be obtained. For definiteness of results the need of specifying the surface character cannot be overstated. In illustration of this it is sufficient to say that the writer has in his possession filaments, the structure of which is such that the surface has a large diffuse reflectivity. Emissive powers for these filaments as ordinarily measured are of the order of 50 per cent. greater than those for polished filaments. Because of these considerations, the determinations of emissive power to be reported have been confined to polished or fairly well polished material.

Effective Wave-lengths of Blue Glass Screens.—A further preliminary test consisted of determining the effective wave-lengths of the blue uviol glass. The red glass had previously been studied by Hyde, Cady and Forsythe.[1] As defined by them, the effective wave-length for a screen for a definite temperature change in the source viewed is that wave-length for which

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

the relative change in monochromatic brightness is equal to the relative change in total brightness for the luminous flux transmitted by the screen. Following a method much as reported previously[1] and as more fully outlined by Langmuir[2] the effective wave-lengths of a single and of a double thickness of the blue glass have been determined for different temperature intervals of black body radiation. By platting the logs of the blue brightnesses as a function of the logs of the red brightnesses for ranges of 100 to 1 of the latter for black body radiation, a very good straight line relation was found. The slopes, using one or two thicknesses of the blue glass against two of the red glass, were respectively 0.745 and 0.706 indicating that if for black radiation for a given temperature interval, the effective wave-length of a screen composed of the two red glasses is, say, 0.665μ, the corresponding effective wave-lengths for the blue glass are respectively 0.495μ and 0.469μ. Unfortunately, the method is insensitive in showing variations in effective wave-lengths. All that may be said is that the effective wave-lengths thus determined are average values. The variations with temperature, for the blue glass using the method described by Hyde, Cady and Forsythe, were found to be fully five times as great relatively as those they found for the red glass. Further considerations due to the lack of monochromatism in the transmission of the screens will be considered in the next subdivision.

CORRECTIONS AND ERRORS.

Difference in Temperature between the Inner and Outer Surfaces.—A simple formula given in a paper by Angell[3] expresses this difference in terms of the thermal conductivity and of ordinary measurable quantities. Letting

r_0 = external radius of the hollow filament,
r_i = internal radius of the hollow filament,
i = current density,
ρ = resistivity,
k = thermal conductivity,
T = temperature,
ΔT = increase in temperature in passing from the external to the internal surface,
E = radiation intensity,
B = brightness,
B_λ = brightness ordinate at λ,

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[1] Astrophys. Jour., 36, p. 348, 1912.

[2] PHYS. REV., II., 6, p. 146, 1915.

[3] PHYS. REV., II., 4, p. 535, 1914.

C_2 = constant in Wien's equation,
ϵ_0 = observed emissive power,
ϵ = corrected emissive power,
subscript (v) refer to filament in vacuo,
subscript (ar) refer to filament in argon,

we have

$$\Delta T = \frac{i^2\rho}{2k}\left(r_i ln\frac{r_0}{r_i} - \frac{r_0^2 - r_i^2}{2}\right).$$

For the filaments used for the greater part of the work r_0 and r_i were respectively 0.66 mm. and 0.38 mm. Taking account of the simply derived relation

$$E = \frac{r_0^2 - r_i^2}{2r_0} i^2\rho,$$

we have

$$\Delta T = \frac{E}{k} \times (0.040 \text{ cm.}).$$

The effect of this ΔT on observed emissive powers is seen when one computes with the aid of Wien's equation, the relative increased brightness of the hole resulting from the existence of this ΔT. Thus

$$\frac{1}{B_\lambda}\frac{\partial B_\lambda}{\partial T}\Delta T = \frac{C_2}{\lambda T^2}\Delta T.$$

Evidently also

$$\frac{\epsilon - \epsilon_0}{\epsilon_0} = \frac{C_2}{\lambda T^2}\Delta T.$$

To obtain values applicable to the gas-immersed filament, it is only necessary to multiply the correction here found by the ratio of the square of the current when thus immersed to the corresponding value for the filament in a vacuum. Values of k and E for tungsten taken from a table appearing in a later subdivision lead to the results given in Table I. The effects of these corrections will be shown later.

Lack of Blackness in Radiation from the Hole.—There are three factors tending toward departure from perfect blackness in this radiation, (1) the presence of the small hole for observing, (2) the existence of a temperature gradient along the tube, and (3) the presence of possible crystal surfaces on the inner surface of the tube.

In connection with the first factor, it is easy to compute the departure from blackness on the supposition of a long tube of uniform temperature with a perfectly matt interior surface. For the smaller of the two sizes of holes specified, and with an assumed emissive power of 0.45, it follows that the radiation will deviate from blackness quantitatively by about

TABLE I.

Emissive-power Corrections for the Temperature Difference between the Internal and External Surfaces of the Filaments Used.

T.	ΔT_v.	$\lambda = 0.665\mu$.			$\lambda = 0.467\mu$.		
		$\frac{T}{B_\lambda}\frac{\partial B_\lambda}{\partial T}$.	$\left(\frac{\epsilon - \epsilon_0}{\epsilon_0}\right)_v$.	$\left(\frac{\epsilon - \epsilon_0}{\epsilon_0}\right)_{ar}$.	$\frac{T}{B_\lambda}\frac{\partial B_\lambda}{\partial T}$.	$\left(\frac{\epsilon - \epsilon_0}{\epsilon_0}\right)_v$.	$\left(\frac{\epsilon - \epsilon_0}{\epsilon_0}\right)_{ar}$.
1500° K.	0.22°	14.4	.002	.004	20.5	.003	.006
2300	1.54	9.4	.006	.007	13.4	.009	.010
3100	5.6	7.0	.012	.013	9.9	.018	.019

0.1 per cent.; for the larger size holes it will be about two times this or 0.2 per cent.

Quantitative computations regarding the effects of the second factor in producing a departure from blackness are difficult. Measurements have been made almost entirely on portions of the filament where the temperature was constant to within a few degrees over lengths on each side for distances of at least five times the internal diameter of the tube. Moreover, measurements intentionally taken where a noticeable temperature gradient existed did not yield results noticeably different. Errors from this source will be more noticeable at the low temperatures than at the high temperatures, because the cooling effects of the supports and leading-in wires are confined to shorter lengths of the filament at the higher temperatures, these lengths being inversely proportional to the heating currents. Errors from this source are probably very small.

The third factor tending away from blackness was a matter of some concern in connection with a certain filament, particularly following the short-circuiting of a resistance in series with it and the consequent melting of a portion of the filament as previously mentioned. Dark irregular patches were noticed within the holes. Later microscopic inspection of the filament showed the surface to be made up of comparatively large crystal surfaces. The accidental orientation of such crystals normal to the line of sight on the inner wall and in line with a hole were apparently the explanation of the dark patches mentioned. The occurrence of a large number of such surfaces oriented irregularly is of course equivalent to a matt surface, such as has been considered already. In the experimental work, by arbitrarily orienting the filament, the spots were eliminated from the field of view. Results with this filament were not noticeably different from those with other polished filaments.

Except in giving the lower values for the emissive power at a given temperature greater weight than the higher values, no correction for these departures have been made.

Lack of Monochromatism in the Light Used.—It is necessary to consider here to what wave-lengths to ascribe[1] the brightness temperature measurements made with the roughly monochromatic screens used in optical pyrometry, and how to correct the emissive power determinations made so that they will uniformly apply to a single wave-length.

Consider in this connection Fig. 2, in which in an exaggerated way curves α, β, γ and δ represent for a given filament at a temperature T, certain spectral brightness B_λ distributions related to the luminous flux transmitted through the pyrometer system including the colored-glass screen at the eyepiece. Let α refer to the black body radiation at the temperature T coming from a hole in the filament wall; β the natural tungsten radiation arising from the adjacent external surface; γ the radiation from a black body having the temperature S, the measured brightness temperature of the natural tungsten radiation; and δ that black body radiation whose relative brightness distribution is the same as that given by β. These diagrammatic distributions assume the pos-

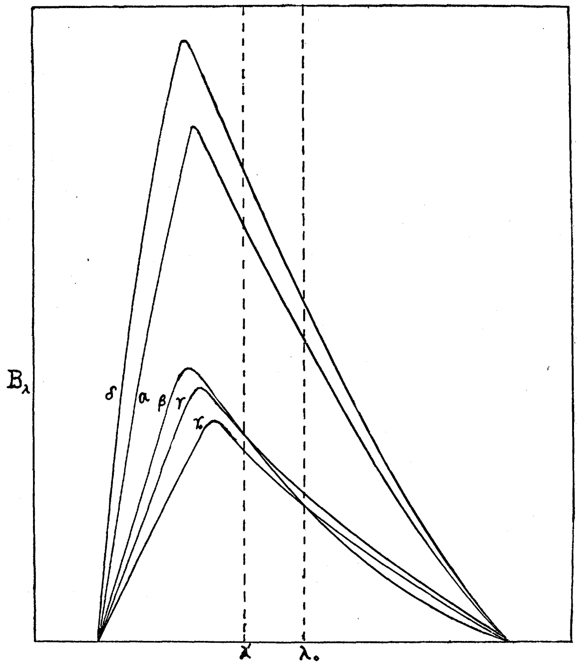

Fig. 2.

A diagram showing various spectral brightness distributions connected with tungsten filaments such as used, which are helpful in determining the wave-length to which to ascribe brightness temperature measurements.

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[1] The writer is in part indebted to his colleague W. E. Forsythe for this development.

sibility of color matching the tungsten radiation with black body radiation. Thus curve δ is, according to Hyde, Cady and Forsythe,[1] the brightness distribution of a black body at a temperature given by the color temperature of the natural radiation. Evidently from the definition of brightness temperature the areas included under curves β and γ are equal. It is also evident that only at the wave-length λ' is the brightness temperature of the natural radiation equal to S, being progressively less than S as the wave-length is increased beyond λ' and progressively greater than S as the wave-length is decreased below λ'.

Representing by ${}_{\alpha}B_{\lambda}$, ${}_{\beta}B_{\lambda}$, etc., values of B_{λ} corresponding to curves α, β, etc. and by ${}_{\alpha}B$, etc., the total brightnesses $\int_0^{\infty} {}_{\alpha}B_{\lambda}d\lambda$, etc., we then have

$$
{}_{\beta}B = {}_{\gamma}B,
$$

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\frac{{}_{\beta}B_{\lambda}}{{}_{\delta}B_{\lambda}} = \frac{{}_{\beta}B}{{}_{\delta}B} = \frac{{}_{\gamma}B}{{}_{\delta}B} = \frac{{}_{\gamma}B_{\lambda'}}{{}_{\delta}B_{\lambda'}},
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where in the first member λ, of course, refers to any wave-length within the range concerned. The last of the above equations according to Hyde, Cady and Forsythe[2] is also the defining equation of the effective wave-length of the pyrometer screen for black body radiation for the temperature interval given by curves γ and δ. It follows therefore that the wave-length λ' to which the brightness temperature S is to be ascribed is the effective wave-length of the screen for black radiation in going from the brightness temperature of the tungsten to its color temperature. In the writer's work λ' for tungsten has varied from 0.6662μ at 1600° K. true temperature to 0.6628μ for 3200° K.

Having once determined λ', the method of determining S_0, the brightness temperature which shall correspond to some common wave-length λ_0 arbitrarily chosen, is simple. It consists in finding the temperature of a black body corresponding to γ_0 (Fig. 2). γ_0 must evidently intersect β at λ_0. The application of Wien's law to a change in which

$$
\frac{{}_{\beta}B_{\lambda_0}}{{}_{\beta}B_{\lambda'}} = \frac{{}_{\gamma_0}B_{\lambda_0}}{{}_{\gamma}B_{\lambda'}} = \frac{{}_{\delta}B_{\lambda_0}}{{}_{\delta}B_{\lambda'}},
$$

gives the result desired. Choosing λ_0 as 0.665μ means in the writer's work that the values of $S_0 - S$ for tungsten for the red light are respectively $+ 0.2°$ and $- 1.4°$ at true temperatures 1600° K. and 3200° K. The corrections for the blue uviol screen are somewhat greater.

In a similar way the wave-length to which to ascribe the emissive

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[1] See following paper.

[2] Astrophys. Jour., 42, p. 294, 1915.

power measurements, may be determined. Imagine another spectral brightness distribution curve added to the somewhat complicated figure, which shall enclose underneath it an area equal to that enclosed by β, and which shall bear the same relation to α that β does to δ. Call this curve β'. The ratio of its ordinates to that of α will everywhere be equal to the measured emissive power. It will cross the curve β at some wave-length λ''. Evidently at this wave-length only is the ratio of the ordinate of β to that of α equal to the measured emissive power. Hence strictly the emissive power measured should be ascribed to λ''. As in the case of λ' just described, λ'' may be shown to be the effective wave-length for the optical system in passing from distribution α to distribution δ. λ'' is slightly shorter than λ'. On considering later the change in emissive power in going from 0.665λ to 0.467λ together with color matching possibilities, it will be seen that the changes in the emissive power in going from λ'' to λ_0 are very small. In this work such corrections at 0.665μ were inappreciable, those at 0.467μ were just appreciable, as will appear later.

At temperatures below 1500° K. in the case of the red light and below 1700° K. in the case of the blue light, single thicknesses of pyrometer screens were used. The corrections to be applied according to the foregoing principles in order to obtain values to be expected if the regular double thicknesses has been usable, are appreciable but not large.

STANDARDIZATIONS.

Any expression of emissive power as a function of temperature necessarily implies a temperature scale which in turn is based on certain standardization points. In the preliminary notice of this paper[1] the temperature scale was based on 1336° K. and 1822° K. as the melting points of gold and palladium respectively. As shown by Hyde, Cady and Forsythe,[2] this with the assumption of Wien's law, which in its effects is indistinguishable in the visible spectrum from Planck's law, leads to a C_2 of $14460\mu \times$ deg. For reasons stated elsewhere[3] our laboratory has abandoned this scale and adopted that one based on 1336° K. as the melting point of gold and $14350\mu \times$ deg. as the value of C_2. This leads to 1828° K. as the melting point of palladium. The importance of stating these underlying bases of temperature scales when one is mentioned should be strongly emphasized. The temperature measurements in the present work were carried out with the aid of a large tungsten

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[1] Jour. of Franklin Inst., 181, p. 417, 1916; Phys. Rev., II., 7, p. 497, 1916.

[2] Astrophys. Jour., 42, p. 300, 1915.

[3] Gen. Elec. Rev.—to appear soon.

filament lamp, which had been standardized as to brightness temperature at the palladium point by W. E. Forsythe, of this laboratory. The calibrations of the sectored disks used in conjunction with Wien's law in determining other brightness temperatures through comparisons with the standardized palladium point were made by a photometric method by F. E. Cady, also of this laboratory and are believed to be known in consequence of repeated determinations and checks with an accuracy of the order of 0.1 per cent.

The method of determining temperatures is given by the following equation

$$ln\, t = ln \frac{{}_0B_\lambda}{B_\lambda} = \frac{C_2}{\lambda}\left(\frac{1}{S} - \frac{1}{S_0}\right),$$

where λ = the effective wave-length,
S_0 = the brightness temperature of the standard (palladium point),
S = the brightness temperature being determined,
B_λ = the brightness ordinate at λ of the spectral brightness distribution curve,
${}_0B_\lambda$ = value of B_λ corresponding to S_0,
C_2 = constant in Wien's equation,
t = transmission of the sectored disk used.

RESULTS.

In the present paper only emissive powers in a direction normal to the surface or nearly so are considered. Values for other angles of emission may be computed with the aid of measured values of the deviation of the radiation from Lambert's cosine law.[1] The values there referred to, however, were obtained on unpolished material and must be so considered.

The experimental values obtained, except that those obtained with single thicknesses of pyrometer glass have been corrected as described so as to refer to double thicknesses, are platted in Fig. 3. Points indicated by difference symbols represent values, as per the accompanying caption, obtained with different filaments or possibly the same filament with the surface renewed by polishing. At room temperature a different procedure was followed. Here for the most part a polished filament previously used by Weniger and Pfund in infra-red measurements and discarded because of pits formed in use, and to some extent some mirror surfaces formed by melting carefully the larger portion of the ends of tungsten terminals in an arc lamp[2] were used. Both types of surfaces had previously the preliminary heat treatment already mentioned. The reflectivity was

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[1] Astrophys. Jour., 36, p. 345, 1912.

[2] Langmuir, II., 6, p. 138, 1915; Luckey, PHYS. REV., II., 9, p. 132, 1917.

measured in the ordinary way, using the pyrometer apparatus as in the previous measurements. The measurements consisted of brightness determinations of a definite spot on a broad lamp filament, first when an mage of the filament was viewed directly, then when viewed reflected from the polished surface, there being, of course, identical optical paths in the two cases, except for the reflection from the polished surface. It was surprising to note how much the image of the broad lamp filament formed at the surface of the discarded polished filament was broken up by fissures, and at the same time that it was impossible to see any such fissures at all when the filament was self-luminous and viewed normally or nearly so. This indicates that for normal emission generally there

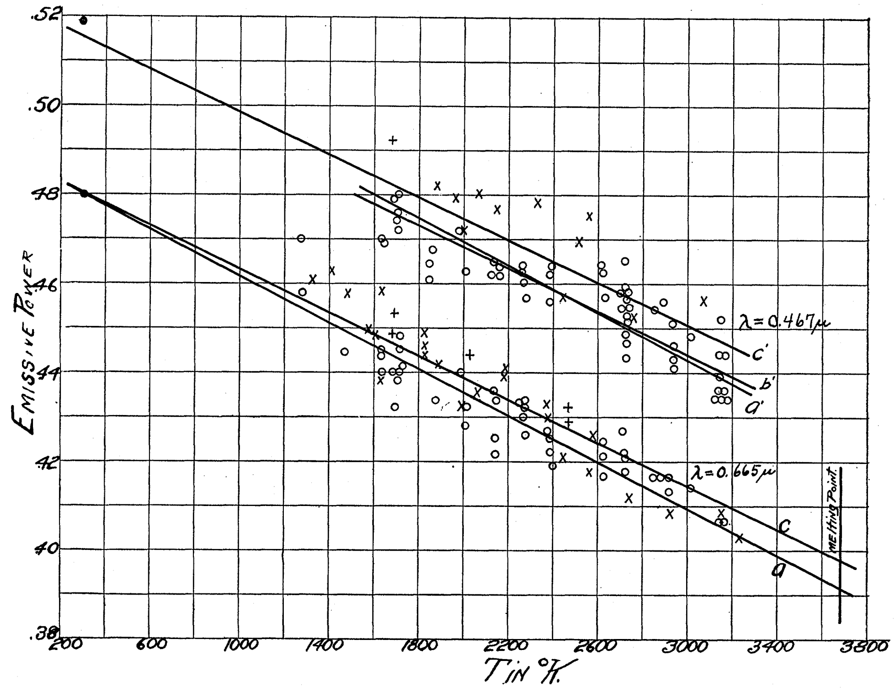

Fig. 3.

Emissive power results for tungsten as a function of the temperature at 0.665μ and 0.467μ.

×, values obtained on unpolished filament in much striated bulbs.

+, " " " polished filaments in much striated bulbs.

○, " " " polished filament in fairly clear bulbs.

●, " " at room temperature by reflection method.

a, *a'*, weighted curves for data obtained.

b', curve *a'* corrected for lack of monochromatism of the uviol glass.

c, *c'*, final curves containing corrections for differences in temperature between interior and exterior surfaces of the filaments.

was no opportunity for blackening of the radiation. A consequence of this is that a rather rough polish of surface only is necessary for emission measurements normally on a self-luminous filament, a fact quite in contrast with the requirements for reflection measurements.

The earlier measurements were made on unpolished filaments in lamp bulbs which, as has been stated, distorted the images somewhat in almost every instance and did not always permit of the selection of holes entirely satisfactorily located from the standpoint of end cooling effects. In the later measurements a partially polished filament was used and the bulb was such as to permit of undistorted images. For these reasons in drawing the curves much emphasis has been given to the later measurements. Further, because errors due to lack of blackness in the radiation from the hole tend toward too high values of the emissive power, the lower values have been given greater weight than the higher values. The heavy lines a and a' in Fig. 3 show the weighted results. Line b' represents the curve obtained when corrections are made for lack of monochromatism in the pyrometer screen transmitting blue light. As stated previously in the case of the red light this correction is negligible. Curves c and c' represent the final emissive power curves in which corrections have been made for the difference in temperature between the interior and the surface of the filament.

When once an expression between temperature and emissive power for a substance is obtained, the use of Wien's equation enables one to express directly the true temperature as a function of the brightness temperature, *i. e.*, the temperature scale for the substance. Thus

$$\frac{1}{T} = \frac{1}{S} + \frac{\lambda}{C_2} ln \epsilon.$$

The relation between T and S for tungsten is given in Table II. by steps of 200°. The highest temperature refers to the melting point of tungsten under atmospheric pressure, further considerations concerning which appear below. The last column of the table indicates the uncertainty in the true temperature of tungsten to be ascribed to an uncertainty of 1 per cent. in the emissive power—that which is considered as probable for the results here presented—when computing the true temperature from brightness temperature and emissive power measurements. It gives at once a method of comparing the scale here obtained with that of others. It is readily seen that Langmuir's scale, when shifted so as to agree as to fundamental characteristics, that is as to the gold point temperature and C_2, and which is based on a constant emissive power of 0.46 agrees with the writer's at 1100° K., but differs from it

Table II.

Temperature Relations for Tungsten on Basis of $C_2 = 14350\mu \times deg.$ *and* $T_{au} = 1336^\circ$ *K.*

S at $\lambda=0.665\mu$.	ϵ at $\lambda=0.665\mu$.	$T-S$.	ΔT in Case $\frac{\Delta\epsilon}{\epsilon}=+0.01$.
1200	.457	56	−0.7
1400	.451	76	1.0
1600	.446	102	1.3
1800	.440	132	1.7
2000	.434	168	2.2
2200	.428	208	2.7
2400	.422	254	3.3
2600	.416	306	3.9
2800	.410	366	4.6
3000	.403	433	5.4
3176 (melting point)	.398	498	6.2

at 2400° K. (the approximate operating temperature of an ordinary 40-watt vacuum tungsten lamp) and at 3675° K. by 18° and 88° respectively. No similar comparison can readily be made with Pirani and Meyer's scale since they used a very different wave-length, but their result of a constant emissive power of 0.44 at 0.532μ is seen from Fig. 3 to be consistent with the writer's only at a temperature in the neighborhood of 2400° K. However, data obtained by Schackelford[1] on emissive powers in the visible region with the aid of helical filaments of various pitches, by Hulbert[2] both as to changes in emissive power with wave-length and with temperature in the ultra-violet region, and by Weniger and Pfund[3] on the reflecting power of tungsten are in very good agreement with those here presented. It is a point worth emphasizing that the tungsten used by them was in the form of wire which had been drawn as in the common commercial method of preparing tungsten filaments while the writer used the squirted paste filaments. Of the remaining individual emissive power values mentioned in the introduction, only that one given by Coblentz for room temperature, 0.474 at 0.65μ, is in good agreement with those presented here.

The Melting Point of Tungsten.

The brightness temperature of tungsten at the melting point as recorded in Table II. represents the mean of the four results shown in Table III. Other results on the melting point of tungsten have been summarized by Langmuir and Luckey in their papers. Only the four

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[1] Loc. cit.

[2] Jour. Frank. Inst., 182, p. 695, 1916; Astrophys. Jour., 40, p. 149, 1917.

[3] Jour. Frank. Inst., 183, p. 354, 1917.

results mentioned have been included, since in connection with these only are the methods sound and the knowledge definite as to effective wave-lengths used and as to the wave-length to which to ascribe the results. The two methods of determining the brightness temperature at the melting point have been well described by Langmuir. The writer has been informed by Langmuir that in his measurements on molten arc terminals, the angle of emission varied considerably from the normal. In consequence of the deviation from Lambert's cosine law, higher values are to be expected than if the surface had been viewed normally. However, both Luckey and the writer in their determinations viewed the surfaces normally or nearly so. This might in part explain the high value obtained by Langmuir on the molten arc terminal. However, there remains as unexplained his still higher value from the filament melt data. Considerations of effective wave-lengths brought forth in a subsequent paper by Hyde, Cady and Forsythe[1] together with certain considerations noted above indicate that Langmuir's results on a basis of $C_2 = 14350\mu \times$ deg. should give as an average 3191° K. for S and that this is to be ascribed to 0.661μ. Reducing the results of all so as to refer to 0.665μ has led to the results shown. An equally weighted average has been accepted for the final result. Making use of the emissive power curve here presented, 3674° K. or in round numbers 3675° K. results as the true temperature for the melting point. The uncertainty as to this, granting the fundamental bases of the temperature scale, would seem to be not greater than 15°.

TABLE III.

Data on Melting Point of Tungsten on Basis of $C_2 = 14350\mu \times$ deg. and $T_{au} = 1336°$ K

Experimenters.	S at $\lambda=0.665\mu$.	Observations Made on
Mendenhall & Forsythe[1]...	3174° K.	Filament melts.
Langmuir[2]..............	3187	Filament melts and molten arc terminals.
Worthing[3]..............	3174	Molten arc terminals.
Luckey[4]................	3169	Molten arc terminals.
Av..................	3176	

[1] Data were obtained at Nela Research Laboratory in summer of 1914 but results have not been published heretofore.

[2] PHYS. REV., II., 6, p. 152, 1915.

[3] Jour. Franklin Inst., 181, p. 417, 1916. PHYS. REV., II., 7, p. 497, 1916.

[4] PHYS. REV., II., 9, p. 132, 1917.

EFFECT ON PREVIOSLY PUBLISHED RESULTS.

The results on thermal and electrical conductivity and Thomson effect previously obtained, expressed in terms of the new temperature scale,

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[1] Loc. cit.

are incorporated in Table IV. The radiation intensity values (see also Fig. 4) in reality are the results of measurements at various times on five filaments as indicated by the different symbols used in the plat. The results in all cases are free from effects due to cool filament terminals. Three of the lamps possessed very fine potential leads of tungsten wire tied to the larger filaments. The remaining two lamps each possessed

Table IV.

Previous Data Corrected to New Temperature Scale.

T in °K.	k in $\frac{\text{watts}}{\text{cm.}\times\text{deg.}}$.	$10^{-8}\times\frac{k}{XT}$ in C.G.S. Units.	σ in $\frac{\text{microvolts}}{\text{degree}}$.	E in $\frac{\text{watts}}{\text{cm.}^2}$.	$\frac{T}{E}\frac{dE}{dT}$.
1500	1.01	2.80[1]		5.7	5.21
1700	1.07	3.06		10.8	5.06
1900	1.12	3.29	−20	18.8	4.93
2100	1.17	3.50	−24	30.6	4.81
2300	1.21	3.69	−28	47.2	4.70
2500	1.25	3.87		69.7	4.60
2700	1.29	4.02		98.9	4.50

[1] It is to be noted that the values originally published were in error by the factor 10.

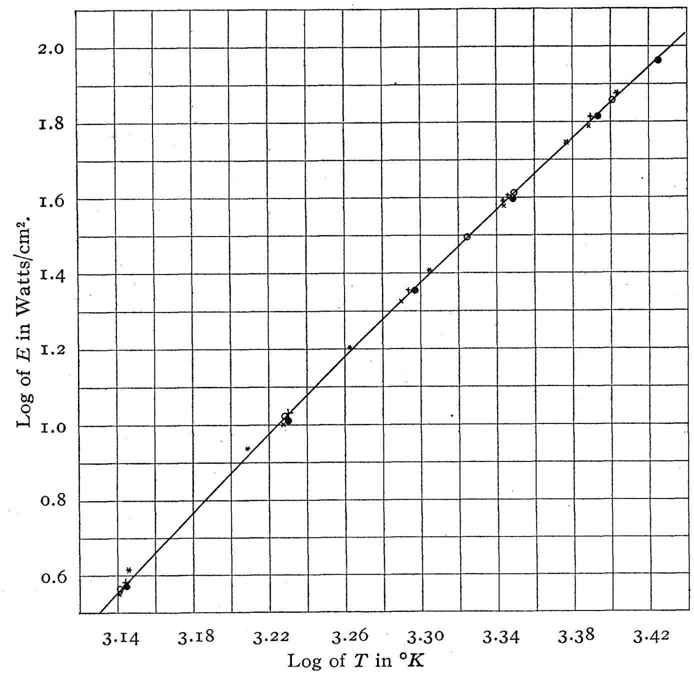

Fig. 4.

Radiation intensity of tungsten as a function of temperature.

two filaments with separate leads which differed only in length, so that by taking differences end effects were eliminated here also. These results may be expressed by the empirical equation

$$\log E = 1.379 + 4.87(\log T - 3.3) - 1.4(\log T - 3.3)^2.$$

It has been assumed that, for practical purposes, the bulbs of the lamps containing these filaments were at negligibly low temperatures. The relative rate of change in emission intensity with relative change in temperature is given under $(T/E)(dE/dT)$ in the table. This quantity for a black body is the exponent 4 occurring in the Stefan-Boltzman equation. The results show a progressive approach toward the black-body radiation in this one respect, but not much significance is to be attached to this since just as fundamental a progressive deviation from black body radiation is shown by the emissive power variation in the visible spectrum.

SUMMARY.

1. A method of determining the emissive power of a substance at incandescent temperatures has been described.

2. A method has been described for determining the wave-lengths to which brightness temperature and emissive power measurements made with the aid of colored glass pyrometer screens are to be ascribed.

3. The emissive power of tungsten at 0.467μ and 0.665μ as a function of temperature have been determined for temperatures up to 3200° K. (Fig. 2 and Table II.).

4. The relation between the true temperature and the brightness temperature at 0.665μ for tungsten has been computed (Table II.).

5. Determinations of the melting point of tungsten have been made. From a consideration of these and other data, 3675° K. ($C_2 = 14350\mu \times$ deg., Tau = 1336° K.) has been obtained as the most probable value for this constant.

6. The radiation intensity as a function of the temperature has been determined for tungsten (Table IV.).

7. Previous data on thermal conductivity and on Thomson effect have been recomputed on the basis of the new temperature scale (Table IV.).

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NATIONAL LAMP WORKS OF GENERAL ELECTRIC COMPANY,
NELA PARK, CLEVELAND, OHIO,
June, 1917.

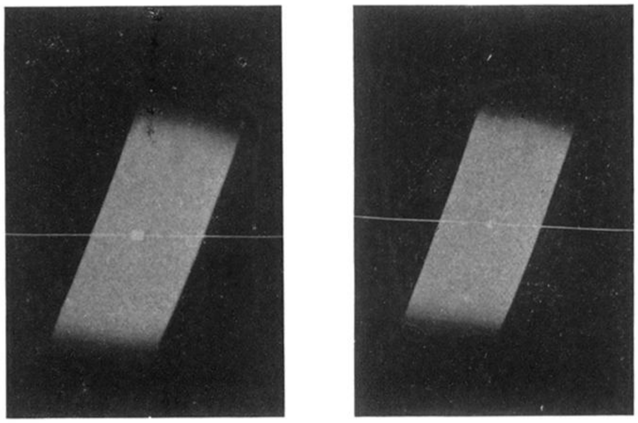

Fig. 1.

Photographs showing the pyrometer filament projected against the hole and the surface as a background for each of the two sizes of holes used.