THE MELTING-POINT OF TUNGSTEN.

BY IRVING LANGMUIR.

SEVERAL years ago (in 1910), during an extended investigation of the characteristics of tungsten filaments, the need arose for a simple means of determining the temperatures of the filaments. The setting up and calibration of special pyrometers would have seriously delayed the work in progress, and it was therefore decided to make as good an estimate of the temperatures as possible from data already available.

The candle power, power consumption, and resistance of the filaments were the quantities of most interest and most easily measured. Any one of these variables might serve as a basis for a temperature scale, but the candle power has marked advantages over the others. The resistance increases relatively slowly with the temperature and is very sensitive to the presence of impurities. The power consumption (wattage) increases more rapidly with temperature, but the law of variation was not definitely known. Furthermore, the wattage cannot be used to determine the temperature in case the filament is surrounded by a gas.

Rasch[1] had developed a relation between the total intrinsic brilliancy (H) of a black body and its temperature, which he expressed in the form

$$\log H = -\frac{A}{T} + B. \tag{1}$$

Haber[2] and Lucas[3] pointed out that this equation could be derived directly from the Wien equation by considering the total visible radiation to be replaced by an equivalent monochromatic radiation.

Crova,[4] however, had shown that with ordinary light sources having a continuous spectrum, it is possible to find a wave-length at which the monochromatic intensities of the different sources are proportional to the total intensities. Crova found this wave-length to be about .58 μ.

Nernst[5] tested Rasch's equation over the temperature range from

[1] Ann. Phys., 14, 193 (1904).

[2] Thermodynamik technischer Gasreaktionen (1905), p. 271.

[3] Phys. Zeitsch., 6, 19 (1905).

[4] Comptes Rendus, 93, p. 512.

[5] Phys. Zeitsch., 7, 380 (1906).

1400° to 2300° and determined the values of the constants A and B. For this purpose Nernst filaments were measured, photometered, and set up in front of a black body furnace and brought to a temperature at which they disappeared against the background. The temperature of the furnace was determined by means of a carefully calibrated Wanner pyrometer, taking the melting-point of gold as 1337° K. (1064° C.) and C_2 of Wien's equation as 14,600. In this way he found that the temperature of a black body could be expressed as a function of its intrinsic brilliancy by the equation

$$T = \frac{11230}{5.367 - \log_{10} K}, \tag{2}$$

where K is the intrinsic brilliancy of the black body in Hefnerkerzen per sq. mm. The temperatures calculated from this equation agreed within 10° with those found by the Wanner pyrometer. The equation was also tested by comparing it with some data given by Lummer and Pringsheim[1] on the total brilliancy of a black body at three temperatures, 1449°, 1597°, and 1707°. In this case the calculated and observed temperatures agreed within 3°.

In order to apply the above equation to the determination of the temperature of filaments, the relative emissivity of the latter as compared to a black body must be known. The reflectivity of tungsten at room temperature (for $\lambda = .579\ \mu$) was found by von Wartenberg[2] to be 48.6 per cent. About the same time, Coblentz measured[3] the reflectivity of tungsten over a wide range of wave-lengths. For the wave-length 0.579 μ his result was 51 per cent., as against von Wartenberg's 48.6. From these results I have estimated that the reflectivity of tungsten would be about 49 per cent. for the Crova wave-length of 0.56 μ.

At the time of the adoption of our temperature scale there were no data available for the reflectivity or emissivity of tungsten at high temperatures, but there was much evidence that in the case of other metals the optical properties were practically independent of the temperature even over wide ranges. This was especially well shown by the papers of Henning,[4] Rubens,[5] von Wartenberg[6] and Hyde.[7]

Even if the emissivity should vary slightly with the temperature, the errors that would be caused by assuming it to be constant would not be

[1] See Rothmud, Z. anorg. Chem., 31, 140 (1902).
[2] Verh. deutschen phys. Ges. 12, 105 (1910).
[3] PHYS. REV., 30, 645 (1910); Bull. Bur. Standards, 7, 202 (1911).
[4] Zeitsch. f. Instrumentenkunde, 30, 1195 (1910).
[5] Verh. phys. Ges., 12, 172 (1910).
[6] Ber. physik. Ges., 12, 121 (1910).
[7] Astrophysical Journal, 36, 89 (1912).

very serious. Thus from equation (2) it can be shown that a 1 per cent. error in the determination of the intrinsic brilliancy or in the assumed value of the emissivity would lead to errors in the temperature determination of only

0.4°	at	1000° K.
0.9°	at	1500
1.5°	at	2000
2.4°	at	2500
3.5°	at	3000
4.7°	at	3500

Therefore, even with a five per cent. change in the emissivity, the errors in the temperature scale would not exceed 24°.

We may then safely assume, as a first approximation, that the reflectivity of tungsten at all temperatures is 49 per cent. (for $\lambda = 0.56\,\mu$). The emissivity is thus 51 per cent.

If we let H be the intrinsic brilliancy of a tungsten filament in international candles per sq. cm., we have

$$K = \frac{H}{0.51 \times 0.9 \times 100} = .0218H.$$

Substituting this in (2), we obtain

$$T = \frac{11230}{7.029 - \log_{10} H}. \tag{3}$$

To determine H experimentally, it is only necessary to measure the candle power and divide this by the effective projected area of the filament. In practice the filament is usually in the form of a single loop, with the two legs nearly parallel. By photometering a filament of known diameter through a horizontal slit placed close to the lamp, and by making a simple geometrical correction, it is thus possible to determine the intrinsic brilliancy (H) with considerable accuracy. By the use of the slit errors due to the cooling effect of the leads are avoided.

The absorption of light by the bulb usually amounts to about 3 per cent. However, this is offset by the departure from Lambert's cosine law. Worthing[1] has shown that "the average brightness of a tungsten cylindrical filament, viewed normally to its axis from a distance, is about 3 per cent. greater than that of the central part." Since the reflectivity of tungsten as determined by von Wartenberg was for normal incidence, it is evident that the 3 per cent. increase in brilliancy from the above cause would just compensate for the bulb absorption. Therefore we may consider that H in equation (3) is the apparent intrinsic brilliancy of the filament, as actually photometered through the bulb.

[1] Astrophys. Jour., 36, 354 (1912).

In determining the intrinsic brilliancy of tungsten filaments in lamps running at voltages considerably above their normal rating, values of H as high as 6,000 candles per sq. cm. were readily obtained. According to equation (3), this should correspond to a temperature of 3460° K. Since there was always perceptible blackening of the bulb under these conditions it is evident that the melting-point of tungsten must be considerably above 3460°. A note to this effect was published in 1911.[1]

Subsequent experiments in which the blackening of the bulb was prevented by inert gases showed that the intrinsic brilliancy at the melting-point is much higher than 6,000 candles per sq. cm.

The following tables gives some results obtained in the course of experiments on the dissociation of hydrogen.[2] The wire used was one of pure tungsten and had a diameter of .00706 cm. The candle power was measured while the voltage applied to the filament was gradually raised. The intrinsic brilliancy at the melting-point was calculated from the photometer setting at the time that the filament melted.

TABLE I.

Lamp No.	Gas in Lamp.		Candles Per Cm.².	Temp. ° K.
	Kind.	Pressure, mm.		
6220–1	H_2	760	7,020	3529
6220–3	H_2	200	6,450	3489
6179–1	N_2	720	7,030	3530
6179–3	N_2	200	7,120	3535
6179–4	N_2	50	7,060	3532
6179–5	—	0	6,750	3510
6321–2	H_2	720	7,050	3531
6321–1	H_2	200	7,350	3551
6435–5	H_2	750	7,460	3558
6394–4	H_2	200	6,850	3518
6220–6	—	0	6,790	3513
			Average.....	3528

In these measurements a Lummer-Brodhun photometer was usually used. To avoid the large differences in color between the two light sources, a blue glass screen was ordinarily placed on the side towards the standard lamp. This glass was calibrated by means of both a flicker and Lummer-Brodhun photometer.

The temperatures gives in the table were calculated according to equation (3).

The mean of these results is 3528° K. but since this method tends to

[1] Trans. Amer. Electrochem. Soc., 20, 237 (1911).

[2] Jour. Amer. Chem. Soc., 36, 1708 (1914).

give low results, weighted mean of 3540° K. would appear more probable. Previous experiments, made in 1911 with filaments in vacuum, had caused us at that time to adopt this figure (3540° K.) as the most probable value of the melting-point.[1]

OTHER DETERMINATIONS OF THE MELTING-POINT.

Determinations of the melting-point of tungsten by other investigators have usually led to lower results.

Waidner and Burgess,[2] by an extrapolation of the current-temperature curve of about 1400°, estimated the melting-point of tungsten to be 3470° K. (3200° C.). A little later[3] they redetermined the melting-point by similar methods and obtained 3350° K. (3080° C.).

Wartenberg[4] determined the black body melting-point of tungsten and by estimating the emissivity, concluded that the true melting-point must lie between 3070° and 3120° K. Subsequently,[5] he made use of his determination of the reflectivity[6] to recalculate the melting-point from the earlier data, and thus obtained 3170° K.

Pirani[7] found, from about 1400° to 2000° K., a linear relation between the logarithm of the temperature and the logarithm of current through a tungsten filament. Extrapolating by means of this relation and applying a correction of about 200°, he obtained for the melting-point 3500° K. ($C_2 = 14{,}500$). Two years later, von Pirani and Meyer[8] determined the black-body melting-point and from this calculated the true temperature by taking the emissivity (at $\lambda = 0.64\ \mu$) to be 51 per cent. Their result was 3270° K. $\pm$ 60° for $C_2 = 14{,}500$.

Shortly afterwards, v. Pirani[9] determined the emissivity of tungsten at high temperatures by means of a Holborn-Kurlbaum pyrometer and found (for $\lambda = 0.64\ \mu$) 48.5 $\pm$ 7.5 per cent., showing that for tungsten the emissivity at high temperatures cannot be greatly different from that at room temperature (51 per cent.).

Forsythe[10] used two different methods in determining the melting-point.

In the first, an optical pyrometer was sighted on the inside of a carbon tube vacuum furnace containing a hairpin filament of tungsten. Thirteen observations of the melting-point gave for an average 3247° K. ($C_2 = 14{,}500$).

[1] This result was published in 1913, Jour. Amer. Soc., 35, 944 (1913).
[2] Bull. Bur. Standards, 2, 319 (1906).
[3] J. physique, 6, 380 (1908).
[4] Ber. deutsch. chem. Ges., 40, 3287 (1907).
[5] Verh. d. physik. Ges., 12, 121 (1910).
[6] L. c.
[7] Verh. d. physik. Ges., 12, 310 (1910).
[8] Verh. d. physik. Ges., 14, 426 (1912).
[9] Physik. Zeitsch., 13, 753 (1912).
[10] Thesis, Univ. Wisconsin, 1911.

In the second method, the black-body melting-point was determined by "balancing the lamp filaments photometrically against the heater tube of the furnace and taking the temperature with the optical pyrometer." In other cases, a tungsten strip was mounted in an exhausted water-cooled brass vessel with windows. Twelve determinations gave an average of 3070° K. for the black-body melting-point. This was then corrected for the difference between black body and true temperatures as found by extrapolation from observations on wedges run up to nearly 3000°. The true melting-point determined in this way was 3300° K., which was considered to be too high.

Ruff[1] has published several results on the melting-point of tungsten

2923° K. Ruff (Ber. d. chem. Ges., 43, 1564 (1910)).
2858° K. Ruff and Goecke (Z. angew. Chem., 24, 1461 (1911)).
2923° K. Ruff (Z. angew. Chem., 24, 2245 (1911)).
3213° K. Ruff (Z. angew. Chem., 25, 1894 (1912)).

as determined in carbon tube vacuum furnaces.

From the results obtained by all these investigators, the most probable value of the melting-point would appear to lie between 3200 and 3300° K.

This, however, is about 300° lower than the value we have found by the measurement of the total intrinsic brilliancy.

SOURCES OF ERROR.

To determine, if possible, the cause of this discrepancy, Dr. E. Q. Adams, of this laboratory, nearly three years ago made careful calculations of the temperature errors that might be due to the use of total brilliancy rather than monochromatic intensity. This calculation was based on Nutting's recalculation of König's data on visibility,[2] Wien's equation, and Coblentz's data on the reflectivity of tungsten.

The equation (2) given by Nernst (and therefore also equation 3) corresponds to a "Crova wave-length" of 0.565 μ (taking $C_2 = 14{,}600$) Dr. Adams calculated that the true Crova wave-length should vary with the temperature of the light source, being about 0.575 μ at 2400° and 0.555 at 3500° K. The errors in the temperature scale due to taking a constant wave-length (0.565 μ) are found never to exceed 20.

A similar conclusion may be drawn from Ives's analysis of Crova's method of photometry.[3] According to Ives, the error in intensity due to taking a constant Crova wave-length of 0.565 μ should not exceed about 3 per cent. in the range from 2000° to 6000° K. We have seen

[1] These results are:

[2] Bull. Bur. Standards, 5, 261 (1909) and 7, 238 (1911).

[3] PHYS. REV., 32, 316 (1911).

that 3 per cent. error in candle power would lead to an error in temperature of only 14° at 3500°.

It is therefore evident that the discrepancy of 300° cannot be due to the use of Crova's method. The other possible sources of error are: (1) a wrong value for the emissivity; (2) a wrong value for the constant in the denominator of Nernst's equation (2).

Even if the emissivity should be 70 per cent. instead of 51 per cent. the melting-point by the total photometric method would still be 3400°. The whole of the discrepancy therefore cannot be explained in this way.

On the other hand, to account for the discrepancy by an error in the constant of Nernst's equation, it would be necessary to assume that the candle powers determined by Nernst were 50 per cent. too low, or that this temperature scale was in error by 44° at the melting-point of gold and 100° at the melting-point of platinum.

The above considerations all tend to confirm the substantial accuracy of the value of 3540° K. as the melting-point.

There does not seem to be any single cause that could account for all the lower values obtained by others. Into many of the methods, however, one factor has entered which tends, according to our experience, to lower the melting-point. This is the presence of vapors of carbon or compounds containing carbon.

In the manufacture of squirted tungsten filaments the latter were sintered by heating to a high temperature in hydrogen. It has often been noticed that the presence of even minute amounts of hydrocarbon vapors in the hydrogen very materially lowers the melting-point and increases the specific resistance. When a filament is quickly raised to its melting-point under these conditions, it is sometimes found that the surface layer melts and runs together in uniformly spaced beads along the wire, showing that the surface layer has a much lower melting-point than the pure tungsten core. These effects are noticed equally well with drawn tungsten wire as with squirted filaments.

Other experiments have shown conclusively that carbon not only lowers the melting-point and raises the resistance, but increases the emissivity. The quantities of hydrocarbon vapor given off by vaseline or stop-cock grease at room temperature in vacuum are sufficient to bring about these changes in a very short time.

The presence of carbon vapors in the experiments of Ruff and in those of Forsythe (1st method) could readily account for a lowering of the melting point of 300° or more. This objection does not apply, however, to Forsythe's determination of the black-body melting-point of the filament of an evacuated lamp. Only the results of one experiment of this

kind are recorded. The presence of carbon vapors, however, may have led to too high a value for the emissivity. Calculating from the difference between the black body and the true temperatures given by Forsythe, the emissivity at the melting-point was found to be 61 per cent. If the value 51 per cent. had been taken instead of 61 per cent., the result would have been 3395°, instead of 3303°.[1]

At a later date, Mendenhall and Forsythe[2] gave the results of determinations of the emissivity of tungsten at high temperatures. They concluded that the emissivity varies from 45 per cent. at 1400° K. to 66 per cent. at 3200° K. In these experiments, however, hydrocarbon vapors were present and there is a possibility that the errors were caused by the opening of a crack at the back of the V made from the two strips of tungsten.

NEW EXPERIMENTS ON MELTING POINT OF TUNGSTEN.

In view of the difficulty of reconciling the value 3540° with the other determinations, it was decided to redetermine the melting-point by methods which would be free from the objections of the total photometric method. An essential part of such work is the determination of the emissivity at high temperatures.

Two methods were used. In the first, the black body melting-point of large filaments in nitrogen was determined and the emissivity was found from measurements on helically wound filaments of various sizes in vacuum and in nitrogen. The second method consisted of measuring the brilliancy of a surface of molten tungsten and simultaneously determining the brilliancy of the image of a second surface of molten tungsten reflected in the first. Thus the reflectivity of molten tungsten was determined directly.

Pyrometer.

The pyrometer used was of the Holborn-Kurlbaum type and resembled very closely that used by Worthing and Forsythe in the Nela Research Laboratory.[3]

To avoid the errors due to diffraction, pointed out by Worthing and Forsythe, no changes were made in the settings of the apparatus throughout the whole series of measurements. Focusing was always done by moving the background lamp.

Screens.

Several nearly monochromatic screens were used in the eyepiece of the telescope.

[1] If the emissivity be taken as 0.46 per cent., the value found as a result of the present investigation, Forsythe's data would lead to a melting-point of 3450°.

[2] Astrophys. Jour., 37, 380 (1913).

[3] PHYS. REV., 4, 163 (1914).

Screen a.—This consisted of a double thickness of Schott and Gnossen's red glass No. 4512. This screen was kindly given me by Dr. Forsythe and is the same as that used in most of his work. Examined with a spectroscope, using a strong source of light (high efficiency tungsten lamp), the transmitted band is seen to extend from .637 to .730 μ, with a maximum at .658 μ. The center of gravity is seen to lie above the maximum, and by observation was estimated to lie at .661 μ.

Screen b.—Wratten and Wainwright green gelatin screen No. 74 (also marked e''). This transmits from .514 to .573 with a maximum at .539.

Screen c.—A combination of Wratten and Wainwright screens 15 and 45. This transmits a narrow symmetrical band with the limits 0.513 and .553. The maximum transmission and the center of gravity appear to be at 0.530.

To determine by independent means the equivalent monochromatic wave-lengths of these screens, the relative brilliancy of a large nitrogen filled lamp (filament straight, not helically wound) was measured by a Lummer-Brodhun photometer at a series of different temperatures, using successively the different screens in the eyepiece.

According to Wien's law, the intensity E_1 of the light of wave-length λ_1, emitted by a body at any temperature T, is given by

$$\log E_1 = a_1 - \frac{b}{\lambda_1 T},$$

where $b = .4343 C_2$ and a_1 is a constant. For any other wave-length λ_2, the intensity E_2, will be given by

$$\log E_2 = a_2 - \frac{b}{\lambda_2 T},$$

where a_2 may be different from a_1.

Eliminating T from these equations, we obtain:

$$\log E_1 = \left(a_1 - a_2 \frac{\lambda_2}{\lambda_1}\right) + \frac{\lambda_2}{\lambda_1} \log E_2.$$

Therefore, by plotting $\log E_1$ against $\log E_2$ a straight line of slope λ_2/λ_1 should be obtained.

The values of E obtained by photometering the large lamp with the various screens were plotted in this way. By assuming that the equivalent wave-length λ of screen c was 0.530, the wave-lengths of the others were found from the slopes of the lines on the plot.

The values for the equivalent wave-lengths found in this way are given in the second column of the following table, together with those estimated by direct spectroscopic examination (third column):

Screen.	By Photometer.	By Spectroscope.
a	0.667 μ	0.661 μ
b	0.537	0.539
c	[.530]	.530

Only the screens *a* and *b* were used with the pyrometer. The wavelengths used in the calculation of the temperatures were those found by the photometric method.

Calibration of Pyrometer.

The first step in the calibration of the pyrometer was the determination of the relation between the luminous intensity of the pyrometer filament and the current flowing through it. This was accomplished by means of three rotating sectors (ratios 1/5, 1/20 and 1/100) and also by comparison with the large nitrogen filled lamp which had previously been photometered through the screens, *a*, *b*, and *c*. Since the lamp had been photometered through a slit which screened off the cooled portions of the filament near the leads, the intensities determined by the photometer should be proportional to those observed in the pyrometer.

The range over which the lamp had been photometered was a wide one, corresponding to temperatures from 1850° to 3040° K. The intensity between these limits increased about ninety-fold with the red screen and nearly 300-fold with the green. By the use of the sectors, it was therefore possible to obtain four curves of the relation between intensity and pryometer current, which overlapped one another to such an extent that the accuracy was much higher than could have been obtained without the sectors. Curves of this character were prepared with both screens *a* and *b*.

The second step was now to determine the current through the pyrometer lamp corresponding to one or more fixed temperatures.

A porcelain tube black-body furnace was set up to calibrate against the melting-point of gold.

Another furnace, consisting of a molybdenum wound alundum tube in a hydrogen atmosphere, was used for the melting-point of copper.

Several determinations of the black-body melting-point of platinum were made.

Finally, the pyrometer was checked against a heavy-filament, evacuated tungsten lamp which had been calibrated by Dr. W. E. Forsythe against a black-body furnace at the melting-point of gold and at the melting-point of palladium.

In comparing the observations at these different temperatures, applica-

tion was made of Wien's law using $C_2 = 14{,}390\ \mu$. This value was chosen as a weighted mean of Warburg's value 14,370[1] and Coblentz's value 14,456.[2]

The temperature scale was then so fixed that the mean of the results obtained for the gold melting-point agreed with Day and Sosman's value, 1062.4° C. In the following table the "observed melting-points" were those found with the pyrometer calibrated in this way. In each case, screen *a* was used.

TABLE II.

Calibration of Pyrometer.

	Observed Melting Point. °K.	Actual Melting Point.	
		°K.	°C.
Gold	1335	1335.4	1062.4[3]
"	1332	"	"
"	1338	"	"
Copper	1358	1356	1083[2]
Platinum (in nitrogen)	2022	2026	1753[3]
" (in nitrogen)	2024	2026	1753
" (in air)	2040	2026	1753
" (in air)	2037	2026	1753
Gold (Fosythe's lamp)	1338	1335.4	1062.4[4]
Palladium (Forsythe's lamp)	1824	1822.2	1549.2[5]

The data for platinum were found by determination of the black-body melting-point of short loops of pure platinum wire (.025 cm. diameter). Three of these were mounted in incandescent lamp bulbs which were exhausted and filled with pure nitrogen. One of these bulbs was accidentally cracked so that air entered the bulb. With each of these lamps, after the platinum wire had been melted, the bulb was broken open and its absorption was determined (usually about 9 per cent.).[6] The fourth determination of the platinum melting-point was made with a loop of wire in the open air. In each case, by careful exploration of the temperatures along the wire while somewhat below the melting-point, it was possible to observe the wire at the place where it ultimately melted.

From these black-body melting-points the "true" melting-points were calculated by taking the emissivity (for $\lambda = .667$) to be 33 per cent., the value recently given by Burgess and Walterberg.[7]

[1] Ann. Phys., 40, 609 (1913).

[2] Jahrb. d. Radioakt., 10, 340 (1913).

[3] Day and Sosman, PHYS. REV., 30, 412 (1910).

[4] Day and Sosman, PHYS. REV., 30, 412 (1910).

[5] Day and Sosman, Journ. de Physique, 5, 899 (1912).

[6] This 9 per cent. includes reflection from the inner and outer surfaces of the bulb and is not all due to absorption. With the photometer the correction for bulb absorption is much less (3 per cent.), because the reflected light is not lost.

[7] PHYS. REV., 4, 546 (1914).

It is interesting to note that the melting-points determined in air are about 15° higher than those found in nitrogen. If, however, the emissivity in air had been 35.6 per cent. instead of 33 per cent., this difference would be accounted for. Through the pyrometer the surface of the platinum wire appeared to be rather rough, or pitted, as compared with the usual surface of tungsten wires. Considering the uncertainty in the emissivity, the agreement with the results of Day and Sosman is very satisfactory.

Having thus calibrated the pyrometer with screen *a* it was now calibrated with screen *b* by setting up the black-body furnace before the pyrometer and comparing the readings obtained with the two screens.

Emissivity of Solid Tungsten.

Upon throwing an enlarged image of the helically wound filament of a nitrogen filled lamp upon a screen, one is struck by the relatively large difference in the intensity of the light from the interior and exterior parts of the helix. With a portable Weber photometer the intrinsic brilliancy of these adjacent parts of the image were found to differ by a ratio as large as 1 : 2. Examination of the image seemed to show that this effect was not due to a difference of temperature between the inside and outside, for there were small areas on the inside which were approximately the same intensity as the outside surface and on the other hand, there were strips along the edges of the outside portions which were nearly as bright as the brightest portions inside.

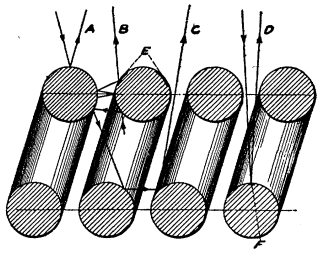

Fig. 1.

The difference in intensity appeared to be due entirely to reflection of light from one portion of the helix to another. In Fig. 1 is represented a longitudinal cross-section of a filament of this kind. The typical paths followed by light rays reflected from such a filament are shown by the letters *A*, *B*, *C*, *D*. In the case *A* there is no opportunity for multiple reflections and brilliancy of the surface is therefore the same as that of a straight filament. The ray *B*, however, is reflected several times and the intensity therefore approaches closely to that of a black-body at the same temperature. It is evident that narrow strips on each side of the wire, as indicated by the heavy lines at *E*, should appear to be of higher intensity. Similarly, the ray *C* is reflected many times, while *D* is only reflected once. Therefore there should be a very narrow strip in the position indicated by *F*, where the intensity is as low as that at *A* and on each side of this the intensity should be high.

Examination of an enlarged image of the filament clearly shows the presence of the dark and light portions in the positions to be expected.

Furthermore, if the helically wound filament is in the shape of a V with the two legs close together, the reflection of one leg in the other is clearly visible and the intensity of the reflected image can be measured approximately.

That the variations in the intensity cannot be due to temperature differences can be calculated readily from the known energy input and from Worthing's data[1] on the heat conductivity of tungsten at high temperatures. Even if we assume the whole of the heat to be generated at the inner side of the wire and all radiated from the outer surface, the difference in temperature for a wire 0.5 mm. in diameter would not exceed about 5° with the filament at 2900°. Actually, however, the effect must be much less than this, especially with the smaller wires and lower temperatures.

A determination of the relative brilliancy of the brightest and darkest portions of a helically wound filament may therefore serve as a basis for calculating an approximate value for the emissivity. However, because of the departure from true black body conditions within the helix, this value will always be somewhat higher than the actual emissivity.

Three lamps were made up with helically wound filaments from wires of different sizes. The filaments were wound so as to be all geometrically similar. Thus, in each case, the mandrel on which the helix was wound had a diameter 1.5 times that of the wire used, and the pitch of the helix was 1.33 times the diameter of the wire, so that the space between consecutive turns was 0.33 of the diameter. The diameters of the three wires were 0.202, 0.305 and 0.635 mm.

Each filament consisted of a V containing 30 turns per leg. The filaments were mounted in large bulbs filled with pure nitrogen. The results obtained with these lamps are given in Table III. The currents given are those which were necessary to heat the helical filament to the temperature indicated. The last column gives the ratio between the brilliancy of the outside part of the helix and that of the brightest portion inside. If strictly black-body conditions prevailed inside the helix, this ratio would be the true emissivity of tungsten. Actually, however, the emissivity must be less than this.

The fact that the emissivity found in this way does not vary appreciably with the diameter of the wire nor with the temperature, is confirmation of our theoretical conclusion that the difference in brilliancy between the inner and outer portions cannot be due to a difference in temperature.

[1] PHYS. REV., 4, 535 (1914).

TABLE III.

Emissivity of Tungsten by Observation of Helical Filaments.

Lamp No.	Diam. of Filament, Cm.	Current, Amps.	Temp. of Filament.	Apparent Screen, *a*.	Emissivity Screen, *b*.
1	0.202	3.04	2040° K.	.50	—
		4.52	2720	.47	—
2	0.305	7.66	2050	.52	—
		12.64	2870	.51	—
3	0.635	16.26	2030	.51	—
		27.1	2820	.52	—
4	0.635	7.7	1430	.507	.512
		15.3	2070	.497	.538
5	0.635	9.6	1450	.465	.481
		16.0	2060	.468	.485
		28.4	2950	.465	.502
6	0.51	15.0	2320	.510	—
		20.0	2900	.486	—
		22.0	3110	.481	—

The helical filaments of lamps 1, 2, and 3 were wound with such a large spacing that the conditions inside the helix did not approach very closely to those in a black-body. To overcome this difficulty as far as possible, lamps 4, 5, and 6 were made up with helical filaments in which the spacing between turns was made as small as was found practicable without too great danger of short-circuiting adjacent turns. The average spacing was roughly $\frac{1}{4}$ of the diameter of the wires. Lamp 4 was evacuated and the tests were made with the lamp in this condition. Lamps 5 and 6 were filled with pure nitrogen. The filaments in each case were aged before the measurements were made, as preliminary tests showed that unless this was done the emissivity was much higher (about 0.60).

The emissivities obtained with lamps 4, 5 and 6 were consistently lower than those found with the first three lamps. Judging from the data obtained with lamp No. 5, the true emissivity must be 0.465, or lower for a wave-length $\lambda = 0.667$ (screen *a*) and 0.485 or lower for $\lambda = 0.537$.

By another method, which will be described below, the emissivity of molten tungsten was measured and found to be .425, while the emissivity of solid tungsten was seen to be distinctly greater than that of the liquid.

From these considerations, we may adopt 0.46 as the most probable value of the emissivity of solid tungsten for $\lambda = .667$. For green light ($\lambda = .535$), we may take the emissivity to be 0.48. These values are in good agreement with Littleton's[1] determination of the reflectivity of

[1] PHYS. REV., 35, 308 (1912).

ductile tungsten at room temperature. Littleton found $R = 0.545$ for $\lambda = .589$, which corresponds to an emissivity of .455 for this wave-length. Evidently, the reflectivity of tungsten does not change appreciably over the whole range from room temperature up to the melting-point.

Melting Points of Tungsten Filaments.

Several lamps were made up containing short filaments (about 6 cm. long) mounted in the form of a single hair pin loop. The bulbs were exhausted while heated an hour to 360° C., filled with pure, dry nitrogen and sealed off.

These lamps were set up, one by one, on the pyrometer, the temperature of the filament was gradually raised to about 3100°.

The temperatures of the filament were not quite uniform, the hottest parts usually being about two thirds of the way from the tip to the lead. The lower portion was cooled somewhat more by convection currents than the upper part, while the upper third was cooled by conduction of heat to the leads. By tilting the lamp slightly, so that one leg of the filament was vertical while the other was somewhat inclined, the temperature of the vertical leg became distinctly higher than that of the other. The hottest point of each filament was located by exploration with the pyrometer and it was thus always possible to sight the pyrometer on the portion at

TABLE IV.

Lamp No.	Filament Diameter, Cm.	Screen *a*.	
		Temp. of Melting Point.	
		Black Body, $\lambda = 0.667$.	True.
7	.0254	3134° K.	3532° K.
8	.0254	3129	3526
9	.0254	3137	3535
10	.0127	3111	3503
11	.0127	3143	3544
12	.0127	3149	3552
Average.....		3134	3532

which melting first occurred. The life of the filaments at the highest temperature was so greatly increased by the surrounding atmosphere of pure nitrogen that the temperature could be raised very slowly to the melting-point. Usually, the actual melting lasted for several seconds, so that accurate pyrometer settings could be made.

After the filament had burned out the bulbs were broken open and the absorption coefficient of the bulb was determined. In every case this was approximately 10 per cent.

Table IV. gives the results obtained in this way. The black-body temperatures have been corrected for bulb absorption. The true temperatures were calculated from black-body temperatures by taking the emissivity (for $\lambda = .667\ \mu$) to be 0.46.

The filaments of lamps 9, 10, and 12 were of exceptionally pure tungsten, while the filaments of lamps 7, 8, and 11 were of "thoriated tungsten"; that is, tungsten made from a mixture of pure tungsten with about $1\frac{1}{2}$ per cent. of thorium oxide. It is evident that the presence of the thorium oxide does not appreciably lower the melting-point.

Determination of Emissivity and Melting-Point by Means of an Arc between Tungsten Electrodes.

An alternating current arc was made to pass between two tungsten electrodes in nitrogen at atmospheric pressure. With sufficiently high current density the ends of both electrodes melted and formed mirror-like convex surfaces in which multiple reflections of the two electrodes could be seen. These surfaces were maintained above the melting-point without perceptible change, for periods of half an hour and more, during which time the intrinsic brilliancy of the molten tungsten and of the

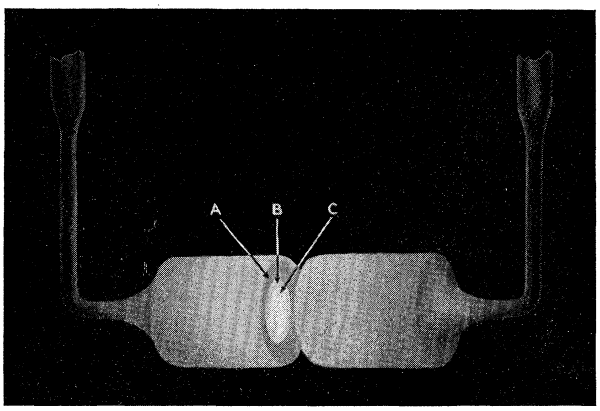

Fig. 2.

successive reflected images were repeatedly measured. This gave a direct determination of the reflectivity of molten tungsten and a simultaneous measurement of the black-body temperature.

The shape and relative positions of the two electrodes are sketched in Fig. 2. The dimensions of the electrodes were approximately as follows: greatest diameter 2.0 mm.; distance apart 1 mm.; least diameter 0.3 mm.; length of large part 2.5 mm.

The extent to which the ends melted could be controlled by adjusting the current. At first only a small wandering spot of molten metal was seen, but with larger currents the end of each electrode became uniformly melted and assumed a slightly convex form in which the opposite electrode formed a beautifully reflected image (B, Fig. 1) of elliptical shape. Inside of this image could be seen a series of concentric ellipses which constituted the successive multiple reflections between the two electrodes. Altogether, four such images could be distinguished, although only the first two were large enough to allow accurate determinations of their intrinsic brilliancy.

The molten tungsten was readily distinguishable in the pyrometer from the solid. In the first place, the solid tungsten always appeared brighter than the molten tungsten in contact with it. Furthermore, the crystalline structure of the solid could be clearly seen, especially if it had previously been melted.

The surface of the molten tungsten was always perfectly uniform and entirely devoid of visible structure.

The arc itself was practically non-luminous. A reading of the pyrometer when set on the space between the two electrodes showed an intrinsic brilliancy only 1.0 per cent. of that of the electrodes. This measurement gives the scattered light in the pyrometer as well as from the arc itself.

If we let r be the reflectivity of tungsten and take as the unit of intrinsic brilliancy that of the surface of molten tungsten at A (Fig. 2), then the brilliancy of the first image (B) should be $1 + r$ and that of the second image (C) should be $1 + r + r^2$. The average of about twenty closely agreeing determinations of intrinsic brilliancy on two pairs of electrodes using the screen a, gave the result shown in Table V.

TABLE V.

Reflectivity of Molten Tungsten

Screen a.

Surface.	Relative Brilliancy.		Calculated $r = .575$.
	Observed.	Theoretical.	
A	1.00	1.00	1.00
B	1.59	$1 + r$	1.575
C	1.89	$1 + r + r^2$	1.905

The observed ratios are in good agreement with the theoretical relation if we take the reflectivity r to be 0.575. This corresponds to an emissivity of .425 for molten tungsten ($\lambda = 0.667$).

In measuring the black-body temperature of the molten tungsten in

determining the melting-point, care was taken to observe a portion of the surface close to the edge of the molten pool, to avoid errors due to superheating of the liquid. The observations were made with the line of sight as nearly normal to the surface of tungsten as possible, for the departure from Lambert's cosine law would otherwise cause errors.

Several determinations of the *black-body melting-point* with the red screen (*a*) gave, after correction for bulb absorption (10 — 17 per cent.), an average of 3124° K. for $\lambda = (.667)$.

This corresponds to a true temperature of 3566° K. if we take the emissivity of molten tungsten (for $\lambda = .667$) to be 0.425.

Only one determination of the black-body temperature was made with the green screen (*b*) and this gave 3322° K. (for $\lambda = 0.535$).

The emissivity of molten tungsten was not measured with the green screen, but if we assume that the *difference* between the emissivity for green and red is the same for molten as for solid tungsten, we may take 0.445 as the emissivity of the liquid for green light. This gives for the true temperature of the melting-point 3550° K. a value 16° lower than that found with the red screen.

DISCUSSION OF RESULTS.

Let us now examine the sources of error involved in the three methods we have used.

The errors of the total photometric method we have already discussed, and our conclusion that this method should not be seriously in error is amply verified by the results obtained by the last two methods. Thus, by the total photometric method we have obtained 3540° as the most probable value for the melting-point, while the *pyrometer* observations on filaments have given an average of 3532° and the observations on the arc electrodes, 3566°.

The main sources of error in the pyrometer methods are:

1. Errors in calibrating at the gold or palladium melting-point.
2. Errors in determining the equivalent monochromatic wave-length of the screens.
3. Errors in the constant C_2 of Wien's equation.
4. Errors in calibrating the foreground filament.
5. Errors in determining the emissivity.
6. Errors in taking the pyrometer readings.

The errors in calibrating against the gold and palladium melting-points are probably not over 2 or 3° at the gold point 1335° or 5° at the palladium point. An error of 1° at the gold point would cause an error of 7° at the tungsten melting-point.

Probably the greatest source of error is in determining the equivalent wave-length for the screens.[1] If we assume that the calibration at the palladium point is correct, then an error of 1 per cent. in determining this wave-length (or a 1 per cent. error in C_2) would cause an error of 32° at the tungsten melting-point. The value $\lambda = 0.667$, which we have taken for the red screen, is perhaps a little too high, although it is certain that it cannot be less than 0.661. There is thus a possibility that this wave-length is nearly 1 per cent. too high. If so, the values for the melting-point should be lowered about 30°.

An error of 1 per cent. in measuring the brilliancy of a filament involves an error of 6° with the red screen, or 5° with the green at the tungsten melting-point.

The melting-points determined by sighting on filaments should tend to be low, whereas those found by observing molten tungsten should be high. The most probable value is the mean of the two. Taking the pyrometer measurements on the filaments and the arc electrodes (with red screen only), we thus obtain 3549°. In view of the fact that the equivalent wave-length of the screen may have been taken too high, we can hardly do better than accept as a final result, the value we have previously obtained by the total photometric method, namely, 3540°.

Taking all the known sources of error into consideration, it would seem hardly possible that the error involved in these results should exceed ± 30°.

SUMMARY.

Observations on evacuated and on gas-filled tungsten lamps indicate that the intrinsic brilliancy of solid tungsten, at a temperature just below the melting-point, is about 7,200 international candles per sq. cm.

According to Rasch's equation, with constants determined by Nernst, and with an emissivity determined by v. Wartenberg, Coblentz and v. Pirani, this intrinsic brilliancy should correspond to a temperature of 3540° K. for the melting-point.

An analysis of the sources of error of this method gives no reason to suspect an error greater than 50°.

Two other methods for determining the melting-point by means of a Holborn-Kurlbaum pyrometer are also used.

In the first method, the black-body temperature of tungsten filaments heated to their melting-point is determined, while the emissivity is measured by observations on helically wound filaments.

In the second method, an alternating current arc is passed between two

[1] At the Washington meeting of the American Physical Society, April 24, 1915, Dr. Hyde gave the effective wave length of transmission of the red glass screen, *a*, as 0.664 μ.

tungsten electrodes placed close together in an atmosphere of nitrogen, and the current is increased until the surfaces of both electrodes are molten. By measuring the intrinsic brilliancy of the molten surface, as well as that of the image of one electrode reflected in the other, the black-body temperature and the reflectivity can be simultaneously measured on the same surface.

The first of these methods gave for solid tungsten an emissivity of 0.46 (for $\lambda = 0.667\ \mu$) and an average melting-point of 3532° K.

The second method gave as the emissivity of molten tungsten 0.425 (for $\lambda = .667\ \mu$) and a melting-point of 3566° K.

From a consideration of the sources of error involved in the determination, it is concluded that the most probable value for the melting-point of tungsten is 3540° K. ± 30°.

The writer wishes to express his indebtedness to Dr. W. E. Forsythe for his help in the calibration of the pyrometer, and to both Dr. Forsythe and Prof. C. E. Mendenhall for valuable suggestions as to the use and construction of the pyrometer. He also wishes to express his appreciation of the valuable coöperation and assistance in all the experimental work rendered by Mr. G. M. J. Mackay and Mr. C. V. Ferguson.

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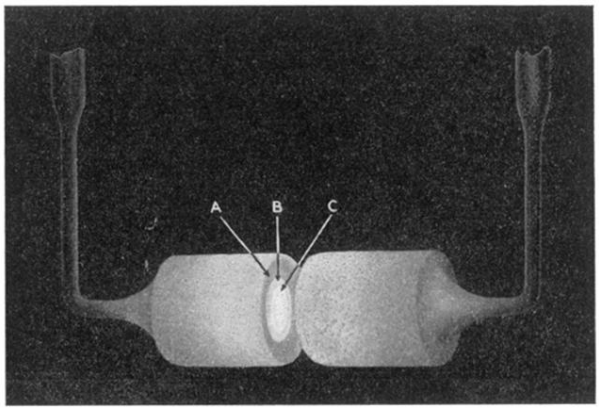

Fig. 2.