A COMPARISON OF ACTUAL AND BLACK-BODY TEMPERATURES

BY CHARLES C. BIDWELL.

THE use of an optical pyrometer to determine the temperature of a metal gives an approximation to the true temperature only when the metal is enclosed, as in a furnace, the walls of which are practically all at the same temperature. The more completely the enclosed region above the metal surface approximates a uniform temperature, the more accurate will be the temperature given by the pryometer. If the metal is in an open crucible with its surface radiating freely into open space and receiving no light from the surroundings there is then a complete departure from black-body conditions. The radiation is selective in such a case and is characteristic of the particular surface. An optical pyrometer sighted upon such a surface will always give temperatures too low. The corrections which must be made to such optical readings have been determined in only a few cases. And the comparisons which have been made by various observers are in rather poor agreement. Recent observations by Stubbs and Prideaux[1] on the emissivity of gold near its melting point and by Stubbs[2] on silver and copper show great changes in emissivity with wave-length. This may account in large measure for the lack of agreement of different observers. The absorbing glasses used in the various pyrometers are never strictly monochromatic. One red glass, admitting a wider range of light than another, may give quite a different value for the black-body temperature. In order to extend our knowledge concerning the laws of selective radiation from metallic and other surfaces there is need of more observations made with monochromatic light. The data submitted in this paper are not intended to meet that requirement fully but they may be of some practical value.

The author has made comparisons of actual and black-body temperatures for several metals through a wide temperature range. A Morse pyrometer, which is of the disappearing filament type, was used with a red absorbing glass. The glass used is one of the best obtainable as regards mono-chromatism. The per cents. of light of the various

[1] Proc. Roy. Soc., Ser. A, Vol. 87, Oct. 1912, p. 451.

[2] Proc. Roy. Soc., Ser. A, Vol. 88, Mar., 1913, p. 195.

wave-lengths transmitted through this glass are given in Fig. 1. The corrections to optical readings which the author has determined for various metals are approximate for any pyrometer in which an absorbing glass transmitting between 0.60μ and 0.70μ is used. They are probably exact only when the absorbing glass is exactly like the one here used. The comparisons are shown for silver, gold, copper, nickel and iron in Fig. 2. Using data from the curves in Fig. 2 the author has computed relative emissivities for these metals through a temperature range of more than 1000 degrees. The relation between relative emissivity and temperature is shown in Fig. 3.

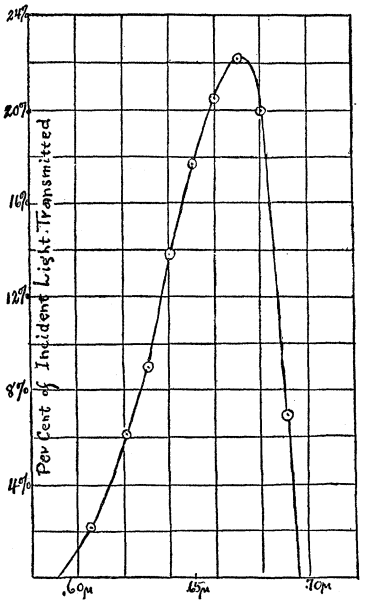

Fig. 1.

Transmission through the absorbing glass used in the Morse pyrometer.

The methods by which actual temperatures were obtained for the various metals in the solid and liquid states, the precautions required in individual cases and the method of computing emissivities are discussed in the following pages.

The pyrometer was calibrated to read "black-body" temperatures first, by sighting into a Reichsanstalt "black-body," the temperature of which was determined by means of a platinum, platinum-rhodium thermo-junction which had been calibrated by the Bureau of Standards. Calibration points as high as 1600° C. were obtained in this way. Beyond this a calibration point was obtained at the melting point of platinum which was taken as 1775° C. A piece of pure platinum was placed in a carbon cavity with a small opening at the top. A small platinum wire projected through this opening from the top of the specimen within. Melting of the specimen was shown by movement of the wire. The cavity was heated electrically and the pyrometer sighted into the opening from above. Additional points between 1600° C. and 1800° were obtained by use of a Wanner pyrometer, for the calibration of which only two points are necessary, the extrapolation being based on Wien's law. The Wanner and the Morse were sighted simultaneously into the black-body cavity in the carbon rod. Calibration points for the Morse were thus obtained at 1625° C., 1725° C. and 1810° C. The point obtained on the melting-point of platinum was in very good agreement with these

points. The author's calibration was found to agree exactly with that furnished by the manufacturer.

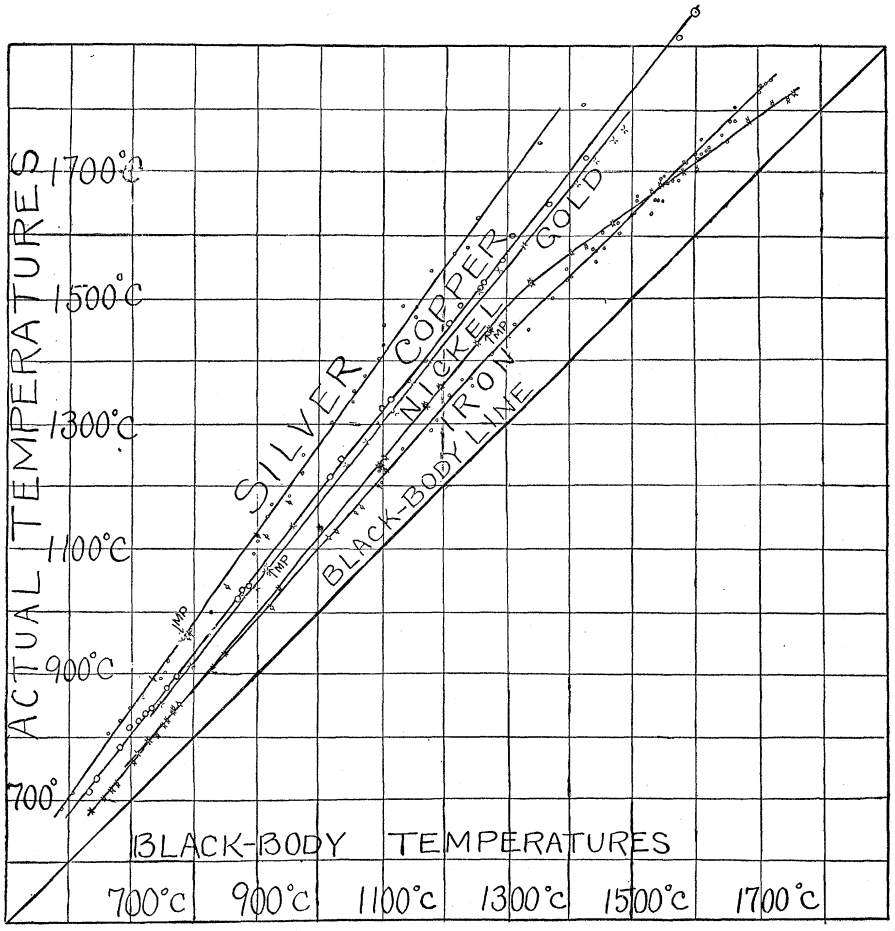

Fig. 2.

Black-body temperatures as compared with actual temperatures for various metals. The deviations of optical readings from actual temperatures are indicated by the vertical heights above the 45 degree, or "black-body" line.

Silver.—Points indicated by small circles with lines were taken with a platinum, platinum rhodium junction encased in quartz. The other points indicated by small circles were taken as described in the text.

Copper.—Points indicated by large circles.

Gold.—Points indicated by crosses.

Nickel.—Points indicated by double circles with crosses were taken by means of a carbon-graphite thermo-junction, the tips of which were frozen into the metal as it solidified from the molten state. The other points for nickel are indicated by small circles with crosses. These were taken as described in the text.

Iron.—Points indicated by small circles were taken on molten iron, those indicated by small circles with lines were taken on solid iron.

The real problem involved in the work was the determination of actual temperatures. The material to be studied was placed in a small cavity in a carbon rod which was heated electrically by a current from a low tension transformer. Observations were made on the free surface of the heated substance and actual temperatures taken simultaneously by means of thermo-junctions or otherwise as described later. Care was

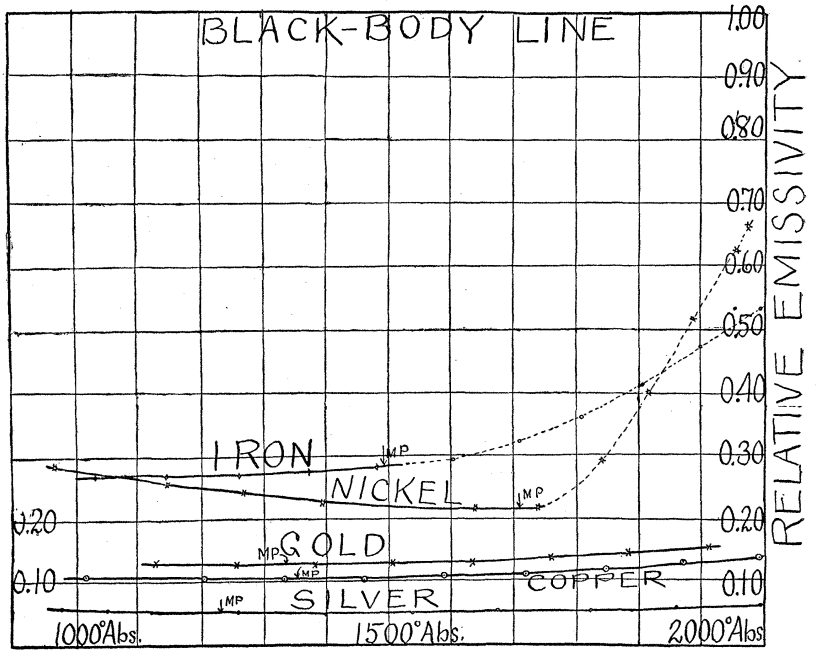

Fig. 3.

Relative emissivity and absolute temperature. (Light of wave-length approximately 0.66μ.)

taken that the material not only filled the cavity but projected above the upper surface of the carbon rod, thus avoiding any chance of light reaching the surface from the surroundings. There were no surrounding walls, the carbon being heated in the open air. Thus the radiation from the surface was that of a body radiating freely into open space and receiving and reflecting no light from its surroundings. The transformer was of 40 kilowatt capacity and used on a 2200-volt circuit. It was capable of stepping the voltage down to 30 in the secondary when the latter was on open circuit. With the secondary short-circuited through the carbon heating rods probably several hundred amperes were ordinarily required. By using carbons of different sizes any desired temperature between 600° C. and 2200° C. could be obtained.

For the determination of actual temperatures a thermo-junction of platinum and platinum with 10 per cent. rhodium, fused into the surface, offered a satisfactory method for solids, but, for convenience and rapidity, optical readings in a hole about 2 mm. deep by 1 mm. wide were taken as giving true temperatures for the surface. The hole was bored with a drill which made the bottom conical. A test of these readings was made by fusing a thermo-junction into the edge of the cavity about flush with the surface. The observations taken in this test are as follows:

Optical Readings in Cavity.	Thermojunction Readings.
1003° C.	990° C.
1005	1000
1015	1010
1050	1045
1075	1060
1130	1125

These readings are seen to agree within the range of accuracy possible with an optical pyrometer. The advantage of the optical method lay in the fact that the pyrometer could be sighted, first on the cavity, then on the surface, then back on the cavity, all within a few seconds and with the one instrument, while thermo-junction measurements involved balancing a potentiometer, which required considerably longer time. And absolutely steady conditions for any length of time were quite out of the question.

In the observations both on solid and molten metals extreme precautions were taken to obtain clear uncontaminated metallic surfaces. In the case of molten metals little trouble was experienced since slag and oxide always float to the edges of the crucible leaving a clear brilliant surface in the middle of the globule. A study of the surface of solid metals brought out the fact that the radiation was altered very greatly by slight changes in the surface. The brilliancy of the polish, the presence of very slight amounts of the polishing materials (rouge, etc.), or an imperceptible film of oxide changed the radiation decidedly. Consistent, reproducible results were only obtained on surfaces procured by solidification from the molten state, the freezing taking place in an atmosphere of hydrogen or nitrogen and the metal kept in such an atmosphere throughout the observations.

With such surfaces no abrupt change in the character of the radiation on passing from solid to liquid or vice versa was observed. A molten metal on freezing will ordinarily be observed to flash up brightly. This does not occur in a reducing atmosphere unless undercooling has taken place.

MOLTEN IRON.

In the case of molten iron a small carbon cavity was immersed in the metal with the opening in the cavity flush with the surface of the iron. Thermo-junction tests showed that cavity readings taken with the pyrometer indicated true temperatures at the surface very accurately. For these observations a large graphite crucible (about 5 cm. deep and 5 cm. inside diameter) was placed in a trough between fire-clay bricks and the trough filled with granular carbon packed tightly around the crucible. Current from the low tension transformer passed through this tightly packed carbon would quickly bring it to any desired temperature. A small carbon rod was fitted into a hole in the bottom of the crucible in such a way as to project vertically up through the middle of the crucible until flush with the top. A small cavity 5 mm. deep by 2 mm. wide drilled into the top of this rod constituted the black-body. The crucible surrounding the rod contained the molten iron. Simultaneous readings were taken at various temperatures in cavity and on iron surface.

As a check on the true temperature, a platinum, platinum-rhodium junction encased in a quartz capillary was pressed into the surface and the temperature readings thus taken compared with the optical readings on the free surface. Extended observations were not possible owing to the softening of the quartz and consequent destruction of the junctions. Two readings which were taken under steady temperature conditions are as follows:

Surface reading....1250° C.	Thermojunction reading....1360° C.
Surface reading....1275° C.	Thermojunction reading....1385° C.

This shows surface readings to be about 110° low. The cavity indicates surface readings to be about 130° low in this temperature region. It is to be expected that the junction readings would not be high enough. The junction was simply laid on the surface and pressed down but not immersed and there must be a temperature gradient from the iron surface through the quartz to the junction. If the junction is pressed beneath the surface, readings depend entirely on the depth of immersion and are no indication of the surface temperature. Hence the cavity readings being slightly higher than the junction readings, as taken above, are to be regarded as probably the truest indication obtainable of the surface temperature. Considerable difficulty was experienced in keeping conditions steady long enough to get satisfactory readings. The best results were obtained while the temperature was slowly rising or slowly falling. The cavity reading was first taken then the surface, and finally the cavity again. The mean of the cavity readings was taken as giving the actual temperature of the surface. The following set of data is a sample of

many runs taken on molten iron. The curve for iron (Fig. 2) records the data of six such runs covering the temperature range from 1200° C. to 1850° C.

Sample Set of Readings on Molten Iron.

Actual Temperatures.		Black Body Temperatures of Surface.
Cavity Readings.	Mean.	
Temp. rising:		
1550°–1580° C.	1565° C.	1440° C.
1580 –1625	1603	1480
1625 –1645	1635	1500
1645 –1665	1655	1505
1665 –1655	1660	1505
1655 –1655	1655	1535
1655 –1685	1670	1530
1685 –1705	1695	1552
Temp. falling:		
1425 –1395	1410	1272
1395 –1320	1357	1240
1320 –1255	1287	1175
1225 –1185	1205	1095

SOLID IRON AND OTHER METALS.

For solid iron the surface studied was obtained by solidification from the molten metal. A small carbon rod was punched into the metal as it was solidifying and in the pasty condition. The frozen surface layer was thus pressed down and the still liquid mass below caused to flow up over it from around the edges and while so doing to solidify. All was carried on beneath burning hydrogen. A brilliant reflecting surface was thus obtained. Readings on such a surface give a curve continuous with the curve for the liquid surface (see Fig. 2). A surface obtained by simply high burnishing does not retain its luster and does not give a curve continuous with that for the molten metal. The cavity used for the "black body" was the hole left by the carbon rod mentioned above. The same method was used for all the metals studied. Only thus could a clear uncontaminated metallic surface be obtained. In some cases the metal was cooled through change of state and down to room temperature in a hydrogen or nitrogen atmosphere and a small hole then drilled into it to serve as a black-body. Only surfaces carefully protected from oxidation give consistent reproducible results.

MOLTEN METALS—GOLD, SILVER, COPPER AND NICKEL.

For gold, silver, nickel and copper in the molten state actual temperatures were determined by means of a thermo-junction of carbon and graphite.

A suitable junction of these materials as finally developed in the course of this work was composed of rods of carbon and graphite about 30 cm. long by 2 mm. diameter clamped side by side but insulated from each other by an air space. The junction was closed across the surface of the metal into which the rods were plunged. The cold ends of the rods were fitted into heavier pieces of carbon and graphite at the farther ends of which were fastened the copper wires which completed the circuit through the galvanometer or potentiometer. For a further description of these junctions with methods of calibration and precautions to be taken in their preparation and use, see following article on "Note on Carbon-Graphite Thermo-junction."

A small globule of the silver or other metal was placed in a cavity bored in the side of a carbon rod, the carbon rod being fitted horizontally into graphite electrodes and heated electrically. The cavity was usually about 10 mm. wide by 6 mm. deep. Enough metal was used to fill the cavity completely with the rounded surface protruding well above the surface of the rod. The thermo-junction points were adjusted to just penetrate the surface. Optical readings were made on the surface as close as possible to the junction. The thermo-electric circuit was completed through a resistance of 10,000 ohms with a high resistance galvanometer shunted around 1000 of these. The galvanometer deflections were calibrated to read temperatures direct. Several runs were made in this way on each metal from temperatures ranging from the melting point to 1900° C. As the junction rods oxidized rapidly in the air above the metal new junctions were required for each run. Hence the data is not dependent upon a single run and a single calibration but in each case on several different junctions each independently calibrated.

On molten silver a set of observations was taken in which actual temperatures were measured with a platinum, platinum-rhodium thermo-junction encased in a very fine quartz tube, the junction being pressed upon the surface of the metal. These readings are, as was expected, slightly lower than the carbon junction measurements (see Fig. 2). On solid nickel a set of observations were taken, in which actual temperatures were measured by means of a carbon-graphite junction which was "frozen" into the metal as it solidified from the molten state. These readings (see Fig. 2) agree well with the observations taken by the "black-body" cavity method.

RELATIVE EMISSIVITY.

The relative emissivities for the different metallic surfaces for the whole temperature range from 600° C. to 1850° C. were computed in the follow-

ing way. If I_a is the intensity of light emitted by any hot body and T_a the corresponding "black-body" temperature, by Wien's law the relation between the two is

$$I_a = c_1\lambda^{-5}e^{-\frac{C_2}{\lambda T_a}} \tag{1}$$

For a full radiator at the same actual temperature we have

$$I = c_1\lambda^{-5}e^{-\frac{C_2}{\lambda T}} \tag{2}$$

Dividing (1) by (2) we get

$$\frac{I_a = e^{\frac{C_2}{\lambda T}}}{I = e^{\frac{C_2}{\lambda T_a}}}. \tag{3}$$

Now $I_a/I = E$ (relative emissivity). We may then write (3) as

$$\log_{10} E = \frac{C_2 \times .434}{\lambda}\left(\frac{T_a - T}{TT_a}\right). \tag{4}$$

If C_2 is taken as 14,500 and λ as 0.66μ then (4) becomes

$$\log_{10} E = 9{,}535\left(\frac{T_a - T}{TT_a}\right).$$

Thus (E) may be determined.

This expression requires the light to be monochromatic and the question now arises whether the light admitted to the pyrometer field is sufficiently monochromatic to justify its use. Fig. 1 shows that about 80 per cent. of the light is between wave-lengths 0.635μ and 0.685μ, with the average at 0.660μ. Computations of the emissivity of nickel at 2078° absolute (using data from the curve, Fig. 2) on the basis that the light is all of wave-length 0.635μ give 0.653 for E. On the basis that the light is all of wave-length 0.685μ we get for E the value 0.673. As the light is fairly evenly distributed between these limits the value of E for the whole band cannot be far from the mean of these values, which is obtained if the light is taken as of wave-length 0.66μ.

A more extreme case is that of silver at 1823° absolute. If all light were of wave-length 0.635μ (E) would be 0.051; if it were all of wave-length 0.685μ, (E) would be 0.063. The value of (E) must lie between these limits and the mean is obtained if we assume the light to be all of wave-length 0.66μ. The error introduced by regarding the light as monochromatic and of wave-length 0.66μ is therefore small and the use of Wien's equation is justified.

Fig. 3 shows the relation between relative emissivities and absolute temperatures. The low emissivity of silver is remarkable. At 1800° C. it radiates like a "black-body" at 1400°. Its emissivity is only about

5 per cent. that of a full radiator. Through the red glass the molten silver appears as a dark spot surrounded by the white hot carbon, yet carbon and silver are at approximately the same temperature.

Molten nickel takes up carbon from the crucible rapidly and beyond 1800° C. becomes a semi-solid pasty mass. On cooling the carbon which was either in solution or combined as carbide crystallizes out as graphite the mass becoming fluid again. The freezing point appears not to be affected by this absorption and expulsion of carbon. It is probable that the emissivity of molten nickel is modified by this absorbed carbon, the sharp rise shown on the curve being due to an actual change in composition which might not occur if the nickel were melted in some other sort of container. The effect was observed with iron also but not at all with gold, silver or copper. On account of this effect the emissivity curves for molten iron and nickel are given as dotted lines since they probably represent changes due to change in composition of the metal.

The relative emissivity which by Kirchhoff's law is the same as the absorptivity is shown to be practically constant for silver, copper and gold through the whole temperature range from 600° C to 1800° C. The values agree also with absorptivities at room temperatures as determined by Hagen and Rubens.[1] The table shows a comparison of Hagen and Rubens' values at 25° C. and the author's values at high temperatures. For silver, copper and gold a knowledge of the reflecting power at ordinary temperature is all that is required for a determination of optical

	Hagen and Rubens—Absorptivity.			The Author.
	0.60 μ.	0.65 μ.	0.70 μ.	0.66 μ (Approx.)
Silver	.074	.065	.054	.055
Gold	.156	.111	.077	.125
Copper	.165	.110	.093	.105
Nickel	.35	.34	.31	[.355–(?)]
Steel	.45	.44	.42	.27–.29 (Iron)

pyrometer corrections at any temperature. The author believes that this has never been verified through a wide temperature range before. Unfortunately for the generality of the above relation, nickel seems to have a temperature coefficient of relative emissivity. Taking the value of this coefficient from the curve as $-$ .000125, the value of the relative emissivity for 25° C. is found by computation to be .355 per cent. The fact that Hagen and Rubens have found practically that value is rather interesting.

[1] Annalen der Physik, 8, 912, p. 1.

All the curves show some evidence of an increase in emissivity at extreme high temperatures.

With regard to emissivity and change of state there is no evidence here of a sudden change occurring, as has been reported by some observers. Attention is called to the data taken on both the molten and solid metals near the melting points, especially for silver, gold and nickel. Except for the movement of slag at the edges of the liquid globule it is impossible to tell optically whether the metal is liquid or solid when near the melting-point. Surfaces artificially prepared, on the other hand, no matter how brilliantly polished always show a sudden drop in emissivity on melting. When a molten metal solidifies *in air* a rise in emissivity occurs as shown by a sudden brightening or flashing up. Evidently these changes are due to the formation of an oxide film or, in the case of the prepared surfaces to the presence of foreign material in the "pores" of the metal.

Cornell University,
February, 1914.