THE EMISSIVITY OF METALS AND OXIDES

I. NICKEL OXIDE (NiO) IN THE RANGE 600° TO 1300°C

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INTRODUCTION

This paper is the first of a series it is hoped to present on the monochromatic and total radiation of oxides and metals. In addition to whatever scientific interest these results may possess, it is believed that the determination of the radiation properties at high temperatures of some of these substances will be of considerable use in technical applications; for example, providing the necessary corrections to apply to the temperature readings of the various types of optical and radiation pyrometers when sighted upon such materials.

HISTORICAL.—Only a few of the recent papers will be mentioned. Waidner and Burgess,¹ Mendenhall,² and Spence³ have determined the departure of the red radiation of platinum at high temperatures from that of a black body, and Henning⁴ has investigated the radiation of this and other metals, spectropyrometrically, over the visible spectrum. The dispersion of the emissivity of solid and liquid gold has been determined in the visible spectrum by Stubbs and Prideaux,⁵ and of solid and liquid copper and liquid silver by Stubbs.⁶ Tungsten, tantalum, and molybdenum have been studied by Mendenhall and Forsythe⁷; platinum, palladium,

¹ Waidner and Burgess, Bur. Standards Scientific Paper No. 55, 46 pp.; also Burgess, Scientific Paper 24, 3 pp.

² Mendenhall, *Astrophys. J.*, 33, pp. 91-97; 1911.

³ Spence, *Astrophys. J.*, 37, pp. 194-197; 1913.

⁴ Henning, *Zs. Instrk.*, 30, pp. 61-75; 1910.

⁵ Stubbs and Prideaux, *Roy. Soc. Proc. (A)*, 87, pp. 451-465; 1912.

⁶ Stubbs, *Roy. Soc. Proc. (A)*, 88, pp. 195-205; 1913.

⁷ Mendenhall and Forsythe, *Astrophys. J.*, 37, pp. 380-390; 1913.

and tantalum by McCauley⁸; carbon, tantalum, and tungsten, chiefly from a theoretical standpoint, by Hyde⁹; tantalum, and tungsten by Waidner and Burgess¹⁰; and iron by Bidwell.¹¹ Coblentz¹² has investigated spectrophotometrically the radiating properties of a number of metals and oxides, mainly in the infra-red. The total emissivity of molten iron and copper has been observed by Thwing,¹³ and of copper by Burgess.¹⁴ Randolph and Overholser¹⁵ have studied the total radiation of various substances up to 600° C and Langmuir¹⁶ of several materials up to 400–600° C.

OBJECT OF THE PRESENT PAPER.—The object of the present investigation has been the determination of the monochromatic and total emissivity of nickel oxide (NiO). This oxide forms in a tough, smooth layer on the surface of nickel when subjected to high temperatures in an oxidizing atmosphere such as air. The total emissivity of NiO and the monochromatic emissivity and its dispersion in the visible spectrum have been measured for several temperatures in the range 600° to 1300° C.

MONOCHROMATIC EMISSIVITY OF NICKEL OXIDE

METHODS OF MEASUREMENT.—Two methods were employed in the determination of the emissivity of NiO for red light, a preliminary method of microscopic melts and a more exact method of direct comparison by a spectrophotometer of the intensity of light emitted by the glowing NiO and by a black body at the same temperature.

METHOD OF MICROSCOPIC MELTS.—Burgess¹⁷ has found that microscopic samples of various substances show sharp and well-defined melting points when placed on a strip of iridium, platinum, or other suitable metal, electrically heated. Such a microscopic specimen readily takes up the temperature of the strip with prac-

⁸ McCauley, *Astrophys. J.*, **37**, pp. 164–182; 1913.

⁹ Hyde, *Astrophys. J.*, **36**, pp. 89–132; 1912.

¹⁰ Waidner and Burgess, *J. de Physique* (4), **6**, pp. 830–834; 1907.

¹¹ Bidwell, *Phys. Rev.* (2), **1**, pp. 482–483; 1913.

¹² Coblentz, *Bur. Standards Scientific Papers* Nos. 45, 91, 97, 105, 131, 152, 156, 191.

¹³ Thwing, *Phys. Rev.* (1), **26**, pp. 190–192; 1908.

¹⁴ Burgess, *Bur. Standards Scientific Paper* No. 121, 9 pp.

¹⁵ Randolph and Overholser, *Phys. Rev.* (2), **2**, pp. 144–152; 1913.

¹⁶ Langmuir, *Amer. Electrochem. Soc. Trans.*, **23**, pp. 299–332; 1913.

¹⁷ Burgess, *Bur. Standards Scientific Papers* Nos. 62, 198; also Burgess and Waltenberg, 205.

tically no difference of temperature existing between the sample and the strip. The melting is almost instantaneous; the minute specimen either rolls up into a ball or spreads out into a thin film, depending upon the material and heating strip used.

In the present work the substances used were NaCl (800°C), Na_2SO_4 (884°), and Au (1063°). The samples were placed on the electrically heated nickel strip C, Fig. 1, previously heated until

FIG. 1.—Method of microscopic melts

a firm coat of NiO had been formed, and the temperature gradually increased by means of the water rheostat D. The melting was observed by the microscope B, and the apparent temperature of the strip at the instant the melting occurred was measured by the optical pyrometer A. This instrument, a Holborn-Kurlbaum type of the Morse pyrometer, was carefully calibrated by two inde-

pendent methods—one, described by Waidner and Burgess,¹⁸ in which a compensated electrically heated porcelain black body of the Lummer-Kurlbaum type is used: and the other,¹⁹ in which a graphite black body is immersed in pots of molten metal. The calibrations by these two independent methods agreed to 1° C. The relation between the true temperature of the strip, the observed or apparent temperature, and the emissivity is expressed by:

$$\frac{I}{T} - \frac{I}{S_\lambda} = \frac{\lambda}{0.4343 c_2} \log A_\lambda$$

where T is the true absolute temperature, S_λ the observed absolute black body temperature for a wave length λ , c_2 the Planck or Wien constant and A_λ the absorption coefficient for a wave length λ . The emissivity is usually defined as the ratio of the intensity of light emitted by a nonblack material to that emitted by a black body at the same temperature. Hence $A_\lambda = \text{emissivity} = \text{absorptivity} = (1 - R_\lambda)$ where R_λ is the reflection coefficient. The most recent determinations of the constant c_2 have been made by Coblenz,²⁰ who obtained as a final value $c_2 = 14\,465$ micron degrees, while the latest determinations at the Reichsanstalt range from 14 374 by Warburg²¹ and associates to 14 400 by Hoffmann and Meisner.²² A rounded value of 14 450 has been used in the present work. The following table presents a summary of results by this method:

TABLE 1
Emissivity of NiO by Microscopic Melts

$[\lambda = 0.65\mu]$

Observations	Material	True temperature	Observed temperature	Emissivity
		°C	°C	
6	NaCl	800	798	0.96 ₂
5	Na ₂ SO ₄	884	880	.93 ₅
8	Au	1063	1055	.90 ₅

¹⁸ Waidner and Burgess, Bur. Standards Scientific Paper No. 55, p. 165.

¹⁹ Kanolt, Bur. Standards Technologic Paper No. 10, p. 8; Foote, Metallurgical and Chem. Engin. 11, pp. 97-98; 1913.

²⁰ Coblenz, Bur. Standards Scientific Paper No. 204, p. 76.

²¹ Warburg, Leithäuser, Hupka, Müller; Preuss. Akad. Wiss., Berlin, Ber., 1, p. 35; 1913.

²² Hoffmann and Meisner, Zs. Instrk., 33, pp. 157; 1913.

SPECTROPHOTOMETRIC METHOD.—Some preliminary data were obtained by comparing the intensity of the radiation from the outside of a nickel tube electrically heated in air with that emitted from a small opening of a diaphragmed inclosure in the center of the tube. By properly locating suitable diaphragms throughout the interior of the tube black body conditions could be obtained quite satisfactorily. It was found more convenient, however, to employ the wedge method of Mendenhall,² the spectrophotometer replacing the optical pyrometers ordinarily used.

The use of spectrophotometer has among others one especial advantage in that slight fluctuations of the heating current affect both the inside and outside surfaces of the wedge alike and hence do not disturb the intensity relation of the two fields. When one pyrometer is used, taking readings alternately inside and out, these fluctuations become serious, especially if the emissivity is high and the difference between the apparent and true temperature of the wedge accordingly small. Two pyrometers, one sighted outside and one inside, and read simultaneously by different observers, only complicate matters on account of the errors of calibration of the instruments and the difference in settings likely to occur with two observers. Moreover, the computation of the emissivity from most pyrometric observations involves a knowledge of λ , the "center of gravity" of the red absorption screen. As has been shown by Waidner and Burgess²³ and by Pirani²⁴ this mean wave length depends upon the character and temperature of the radiating source sighted upon, and upon the visibility curve of the individual observer. It is not a true monochromatic transmission, or a narrow band, but a band containing nearly all the spectrum. This difficulty does not occur with the Wanner pyrometer or the spectral pyrometers of Mendenhall and of Henning in which the absorption screen is replaced by a dispersing prism. But even with a spectral pyrometer it is probable that the measurement of the difference of two temperatures which are nearly identical gives rise to greater error than the direct determination photometrically of two light intensities which are quite different.

²³ Waidner and Burgess, see 18, *idem.*, p. 175.

²⁴ Pirani, *Deutsch. Phys. Gesell. Verh.*, 1913, pp. 826-838.

Fig. 2 illustrates the optical arrangement used with a spectrophotometer of the Lummer-Brodhun type. It was found necessary on account of stray light to replace the Lummer-Brodhun cube by a silver-strip cube. The field of view thus obtained is represented by P. The dispersion of the spectrophotometer prism was calibrated by the spectral lines of Na, He, and several Fraunhofer lines. The spectral width of the emergent cone of

FIG. 2.—Spectrophotometer method

light was about $40\text{ }m\mu$ in the red and $20\text{ }m\mu$ in the violet. In making a series of observations the wedge was usually replaced by a source of light of approximately equal intensity in the direction AC and AD. The collimator slits were then adjusted until a match was obtained at P. The wedge was then inserted in the position A and a new match effected by adjusting the sector disks C and D without disturbing the collimator slits. Sector D was

used for preliminary adjustment when necessary. It consists of a 7-step disk with transmissions of 0.95, 0.90, 0.80, 0.70, 0.60, 0.50, and 0.40. The final adjustment was made with the disk C. This sector was designed by Brodhun²⁵ and is so constructed that any angular opening from 0 to 200° French system can be made while rotating at full speed, and by an arrangement of mirrors the scale in motion may be read to 0.01°. After a series of readings have been taken with the wedge in position A, the wedge is turned through 90° to position B and a new series made. A previous test

FIG. 3.—Method of mounting and heating wedge

has shown that both outer sides of the wedge emit with the same intensity. The zero adjustment of the spectrophotometer is thus obviated. The final intensity relation is obtained by taking the square root of the product of the intensity relations in positions A and B. Readings were taken in this manner for several temperatures, and color varying from $\lambda = 0.5\mu$ to 0.7μ .

Fig. 3 shows a sketch of the furnace used for holding and heating the wedge. The furnace was constructed a little more elaborately than necessary for this particular investigation for the reason that it will be employed subsequently for metals and oxides

²⁵ Brodhun, Zs. Instrk., 24, p. 313; 1904.

where it is desirable to use vacuum or an atmosphere of nitrogen or hydrogen. The entire furnace is water jacketed and so mounted that it may be conveniently rotated about its point of support in order to bring into the line of sight any one of the three windows illustrated in the figure. The wedge was mounted between a fixed water cooled contact A and a movable double spiral, water cooled, spring contact B. Such a mounting satisfactorily takes care of the expansion of the wedge on heating.

FIG. 4.—Magnified section of wedge

RADIATION FROM A WEDGE-SHAPED CAVITY.—Mendenhall,² following the method used by Féry²⁶ relative to the emission from conical cavities has shown that a wedge-shaped cavity of small angle emits practically black-body radiation. With a thin wedge there is practically no difference of temperature between the inside and outside surface. In the present work the wedge, heated in air, becomes coated with a thin layer of oxide which undoubtedly has a lower heat conductivity than the Ni. It is necessary to know what effect this thin homogeneous layer has on the temperature gradient through the wedge. The maximum gradient

effect can be obtained as follows. Assume that the oxide is non-conducting electrically and that the entire heat loss takes place on the outside of the wedge only. Fig. 4 represents a magnified section of the wedge:

T_0 = inside absolute temperature.

T_1 = absolute temperature at boundary of Ni and NiO.

T_2 = absolute temperature of outside surface.

p = thickness of Ni.

e = thickness of NiO.

²⁶ Féry, *Compt. rend.* 148, pp. 777-780; 1909.

k = heat conductivity of Ni.

q = heat conductivity of NiO.

E = potential drop along 1 cm of strip.

I = current density, i. e., current per cm^2 of cross section.

b = total breadth of wedge, both outer sides.

dT/dx = temperature gradient through Ni.

R = specific resistance of Ni.

Q = quantity of heat passing through oxide per cm^2 of surface per sec.

$$(1) \quad Q = q \frac{T_1 - T_2}{e} = I^2 R p = \text{amount of heat developed per second in section of Ni } 1 \times 1 \times p \text{ cm}^3.$$

$$(2) \quad T_1 - T_2 = I^2 R p e / q$$

Consider a thin lamina 1×1 cm in center of the nickel strip. Total energy per second developed in $1 \text{ cm}^3 = EI$ watts. Energy per second developed in a lamina $1 \times 1 \times x \text{ cm}^3 = xEI$ watts.

$$(3) \quad xEI = -kdT/dx$$

integrating between the limits $x=0$ and $x=p$

$$(4) \quad EI p^2 / 2k = T_0 - T_1 = I^2 R p^2 / 2k$$

$$(5) \quad T_1 = T_0 - I^2 R p^2 / 2k$$

substituting in (2)

$$(6) \quad T_0 - T_2 = I^2 R p (p/2k + e/q)$$

or

$$(7) \quad T_0 - T_2 = EI p (p/2k + e/q)$$

The thickness of the Ni employed was about 0.010 to 0.015 cm. The oxide thickness varied from 0.002 cm after one hour heating at 1100°C to 0.005 cm after five hours. The heat conductivity, k , of nickel is known from Angell's²⁷ determinations, but no observations appear to exist for q . Even though q is assumed

²⁷ Angell, Phys. Rev. (1), 83, pp. 421-432; 1911.

0.1 of k the second term in brackets in (7) is much greater than the first for a value of $e=0.003$ or 0.005 cm. Since the variation of p with time of heating is small one may eliminate the e/q term by taking readings with successively thinner oxide layers and extrapolating the curve thus obtained to zero thickness or zero time of heating. When this is done T_2 becomes theoretically equal to T_1 ; hence:

$$\text{For zero time} \quad T_0 - T_2 = EI p^2 / 2k = \delta T.$$

Let I'_2 refer to the intensity of light emitted by the NiO surface at a temperature T_2 .

I_0 refer to the intensity of light emitted by a black body at a temperature T_0 .

I_2 refer to the intensity of light emitted by a black body at a temperature T_2 .

The ratio of intensities measured by the spectrophotometer is:

$$(8) \quad \frac{I'_2}{I_0} = \frac{I'_2}{I_2 + \delta I}$$

The intensity ratio desired is:

$$(9) \quad I'_2 / I_2$$

$$(10) \quad \text{By Wien's law: } I = c_1 \lambda^{-5} e^{-c_2 / \lambda T}$$

$$(11) \quad \text{hence } \delta I = I \frac{c_2}{\lambda T^2} \delta T$$

substituting in (8), observed emissivity is as follows:

$$(12) \quad I'_2 / I_0 = \frac{I'_2}{\left(1 + \frac{c_2}{\lambda T_2^2} \delta T\right) I_2}$$

$$(13) \quad \text{True emissivity} = \left(1 + \frac{c_2}{\lambda T_2^2} \delta T\right) \cdot (\text{observed emissivity}).$$

$$(14) \quad \text{Correction factor to observed data} = \left(1 + \frac{c_2}{\lambda T_2^2} \delta T\right)$$

Equation (14) represents therefore the correction which may be applied to observations on a film of oxide of negligible thickness.

The energy dissipated in the wedge is lost by end conduction, radiation, and convection. In the present work the air pressure inside the furnace was atmospheric, and hence the convection loss was high. Observations showed that the total energy loss from the wedge was from two to three times the loss by radiation. A part of the total energy loss must come directly from the wedge-shaped cavity. The small amount lost by radiation from the cavity may be computed, but it is difficult to determine the nature of the convection currents in this V-shaped opening. Equation (14) was derived on the assumption that all the energy was lost from the outside surface of the wedge. The radiation and convection losses from the interior of the wedge and the loss by conduction at the ends will lower the temperature gradient through the nickel as computed from the total power consumption, and hence lower the magnitude of the correction factor. The magnitude of the correction as derived above varies from 0.5 to 2 per cent for the experiments in question. On account of its being in reality very much smaller, and the exact correction not being conveniently determinable, no correction whatever has been applied to the data. It is probable that the uncorrected values are more accurate than the values increased by this maximum correction. Some slight advantage might have been gained in using a high vacuum, thus reducing the convection loss and the temperature gradient effect. Determinations in air at atmospheric pressure, however, are believed to be of sufficient accuracy and of greater interest.

METHOD OF OBSERVATION.—The nickel strip of dimensions about 6 by 9 by 0.014 cm was folded into a 10° wedge 3 by 9 cm, mounted in the furnace and electrically heated in air for several minutes until a smooth, tough coat of oxide formed. The current was so regulated that the temperature measured by the optical pyrometer remained constant throughout the series of observations. Spectrophotometric measurements were made at 10 to 12 wave lengths in the visible spectrum with the wedge first in position A and then in position B. The time of the observations was

recorded, counted from the initial flowing of the current. For each of a series of times varying from 0.2 to 6 hours, a spectral curve of emissivity was plotted. In all cases the relation E_λ vs. λ was practically linear. This operation was repeated independently for a number of different wedges. The emissivity observed at various times, for the three wave lengths $\lambda = 0.5, 0.6$, and 0.7μ

FIG. 5.—“Apparent” monochromatic emissivity as a function of the oxide thickness

(read from the spectral curves) was plotted, time vs. apparent or observed E_λ .

Fig. 5 represents a typical example of this procedure. Here are shown the independent determinations on 4 different wedges at an average temperature of 1159°C , for the above wave lengths. Each point is taken from a spectral curve observed at the indicated times. Within experimental error, a straight line may be drawn through the points. This line extrapolated to zero time represents the intensity relations for an extremely thin oxide layer, an ideal oxide layer which is thick enough to be opaque,

and hence one which possesses the same optical properties as a thick layer, but one so thin that the temperature gradient through it is practically nil. The extrapolated value of the intensity ratios is taken as the true emissivity of NiO. This process was repeated for 3 other temperatures, namely, 936, 1058, and 1255° C. A number of wedges were employed, each one being operated at a single temperature only. The reason for this is not that heating at, say, 1255° alters the character of the surface so that different values would be found on again lowering the temperature to 936°, but simply to avoid complicating the rate of formation of the oxide and thus altering the temperature gradient throughout the oxide layer. A number of observations were taken to justify the statement that the emissivity of the oxide does not depend upon its previous heat treatment, at least within the limits of the present experimental error.

CHARACTER OF THE OXIDE (analysis by J. R. Cain).—The nickel used contained a small amount of iron. One sample showed 0.8 per cent Fe. The oxide formed on heating in air is NiO with the above proportion of iron as FeO. When the black, tough coat of NiO was removed, a minute green film was detected, deposited on the nickel surface. This was so thin and in such small quantity that it was not possible to analyze it. It is very likely Ni_2O_3 , and is immediately converted into the black oxide NiO on heating in air. The existence of Ni_2O_3 , however, is questioned somewhat in Moissan's and Gmelin-Kraut's treatises, and its properties are not fully described.

RESULTS.—Fig. 6 presents the final observations on the dispersion of the emissivity of NiO in the range $\lambda = 0.5$ to 0.7μ for the temperatures 936, 1058, 1159, and 1255° C. Over this range of the spectrum the emissivity is found to increase with increasing wave lengths. The type of curves suggests the presence of an absorption band in the early infra red, but one which is probably broad and not well defined.

Fig. 7 illustrates the variation of emissivity with temperature for a wave length $\lambda = 0.65\mu$. The three points obtained by the method of microscopic melts lie well upon the curve determined by the spectrophotometric measurements. It has generally been

assumed that the emissivity in the visible spectrum of pure metals is independent of temperature. Mendenhall and Forsythe,⁷ however, have questioned this and have observed marked temperature coefficients of A_λ with several metals. For $\lambda=0.658\mu$ they found that the emissivity of molybdenum, tantalum, and carbon decreases with increasing temperature, while for tungsten an increase of emissivity with increasing temperature takes place. It is well known that the emissivity of the rare earth oxides is dependent upon the temperature. There is accordingly no reason for expecting the monochromatic emissivity of NiO to be independent

FIG. 6.—Monochromatic emissivity vs. wave length

of temperature. That the emissivity of NiO for any wave length in the visible spectrum decreases with increasing temperature is firmly established by the present observations.

In Fig. 8 are given the corrections in degrees centigrade which must be added to the temperature observed with an optical pyrometer using red light ($\lambda=0.65\mu$), when sighted on NiO, in order to obtain the true temperature of the material. These corrections are small, amounting to only 20° at 1300°C .

In Table 3 are given the numerical values of these corrections to be applied to the observed temperatures, and the corresponding true temperatures, on both the Centigrade and Fahrenheit scales.

THE TOTAL EMISSIVITY OF NICKEL OXIDE

METHOD.—A strip of sheet nickel usually about 6 by 15 cm in size, mounted vertically, was electrically heated in air until a uniform, fairly thick coat of oxide was formed. Upon this strip were sighted normally radiation pyrometers of various types. The apparent temperatures for $\lambda=0.65\mu$ were obtained by means of an Holborn and Kurlbaum pyrometer and corrected to true temperatures according to the curve in Fig. 8. Observations were

FIG. 7.—Monochromatic emissivity ($\lambda=0.65\mu$) vs. temperature

taken for a large number of different temperatures. The same strip could be used over the range 600 to 1200° and readings made at 600° both before and after heating to 1200° agreed in all cases. The previous heat treatment of the strip accordingly had no effect. In general each pyrometer was used for a series of readings on 4 or 5 different strips. Three sets of readings were taken with pyrometers sighted on a 2.5-cm nickel tube electrically heated. The results were the same as for the strips.

THE PYROMETERS.—Ten different pyrometers were employed. Three of these were of the Thwing²⁸ type and seven of the Féry²⁹ type. Two of the Thwing pyrometers were the ordinary long tube receivers with the thermoelement located at the apex of an aluminum reflecting cone. The other was the so-called permanent installation type in which the diaphragms are open to the air to prevent heating. In this instrument the open end of the cone was

FIG. 8.—Corrections to optical pyrometer

covered by a thin mica window. Six of the Féry pyrometers were thermoelectric instruments with gold mirrors; the other was a Féry Spiral pyrometer, in which the thermoelement is replaced by a bimetallic spring which on expanding or contracting operates a movable pointer over a scale graduated in terms of temperature.

The relation between temperature and emf of the thermocouple type radiation pyrometers may be expressed by the empirical equation $e = a (T^b - T_0^b)$ where e is the emf developed by the

²⁸ Thwing, J. Frank. Inst., 165, pp. 363-370; 1908.

²⁹ Féry, Engineering, 84, pp. 539-540, 1907. Bull. d. Seances Soc. Franc. d. Physique, 1907, pp. 186-188.

thermocouple, the cold junction being at T_{abs} and the hot junction a few degrees above this, depending upon T the absolute temperature of the black body upon which the pyrometer is sighted, and b is an empirical constant of approximate value 4.

The pyrometers³⁰ were calibrated by sighting into a (15 by 6 cm inside measurement) diaphragmed graphite black body mounted in a 60 by 8 cm platinum wound furnace, inclined 30° to the horizontal to mitigate air circulation. Kaolin diaphragms of proper aperture were located at various distances along the furnace to further prevent air circulation. The temperature of the black body was measured by two platinum-rhodium thermocouples which were calibrated in terms of the melting points of zinc, antimony, and copper. The readings of these couples were checked by an Holborn and Kurlbaum pyrometer sighted into the graphite black body. Exploration with a thermocouple through the 15-cm length of the black body showed a satisfactory temperature distribution (variations of less than 5° at 1300°). The readings of the optical pyrometer and of the thermocouples agreed to at least 5° , showing that black body conditions were sufficiently well obtained.

Two of the Féry instruments were used both with and without the diaphragm attachment, so that in reality 12 radiation instruments were employed.

The question of blackness of the receivers will be discussed in the paper mentioned above. It is sufficient to state here that only the selective absorption (i. e. variation of absorption or reflection coefficient with wave length) is of importance. The gold mirror³¹ of the Féry pyrometer reflects uniformly about 96%³² of the heat radiation from 1 to 14μ . In the temperature range 600° to 1200° C only a small amount of the radiation can be affected by the selectivity of gold in the visible spectrum. The receivers are accordingly black or more accurately "gray," as far as the requirements of the present experiments are concerned.

³⁰ The subject of radiation pyrometry is one which has been briefly reported upon by the authors (Phys. Rev. (2), 2, pp. 77-8) and it is hoped to present the completed paper very shortly under the title "Some Characteristics of Radiation Pyrometers." For the reason that the various points which come up in the use and calibration of radiation pyrometers will there be treated in full, a complete discussion will not be given here.

³¹ Reflecting Power of Gold, Smithsonian Physical Tables.

³² Whipple, Engineering, 90, p. 142; 1910.

THE APPLICATION OF RADIATION PYROMETERS TO THE DETERMINATION OF EMISSIVITY.—If E denotes the total emissivity of an approximately nonselectively radiating material at an absolute temperature T , and S the apparent absolute temperature of this material observed with an approximately nonselective receiver of the radiation pyrometer type, we have

$$(1) \quad E = \frac{S^4 - T_o^4}{T^4 - T_o^4}$$

Above 600° C the error involved in omitting the T_o term is negligible. For example, if the emissivity is about 0.5, the error in E , arising from neglecting $T_o = 300$, is about 0.007 at 600° C and 0.0002 at 1300° C. At higher values of E the error is still smaller. Hence it is possible to write:

$$(2) \quad E = S^4/T^4$$

Expressed in terms of emf where e denotes the emf developed by a thermoelectric radiation pyrometer sighted on a black body of temperature $T^{\circ}\text{abs}$ and e' the emf developed when sighted on a nonblack approximately nonselectively radiating substance of apparent temperature $S^{\circ}\text{abs}$ and true temperature T° , (2) becomes;

$$(3) \quad E = (e'/e)^{4/b}$$

where b is the characteristic exponent of the empirical equation $e = aT^b$.

Equation (3) was used in the computation of the emissivity determinations for all the pyrometers except the Féry Spiral, for which equation (2) was employed.

RESULTS.—Table 2 presents the data upon total emissivity for a series of temperatures from 600 to 1300° C. Each horizontal line represents the observations by any one instrument, the values being taken from a smooth curve of emissivity vs. true temperature of NiO for the indicated pyrometer. This curve was determined by from 20 to 60 independent observations at various temperatures and on several nickel strips. The averages of the determinations by the different pyrometers are given in line 13.

TABLE 2
Total Emissivity, Summary of Observations

Weight	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	Temperature °C Pyrometer	Expo- nent
1	0.74	0.75	0.76	0.76	0.77	0.78	0.79	0.80	0.81	0.84	0.89	0.94	0.97	.....	0.93	Thwing 983 box receiver	4.32
2	.....	.....	.55	.59	.62	.64	.65	.66	.67	.71	.77	.85	.89	.....	0.92	Thwing 984 tube receiver	3.56
2	.....	.60	.62	.65	.67	.69	.70	.72	.74	.77	.81	.86	.90	.92	.92	Thwing 985 tube receiver	3.68
2	.....	.....	.74	.76	.78	.80	.82	.84	.85	.87	.89	.90	.90	.88	.....	Fery thermoelectric 10509	3.96
2	.47	.55	.63	.70	.77	.80	.83	.84	.84	.85	.85	.84	.83	.81	.78	Fery thermoelectric 5967	3.87
2	.56	.63	.68	.73	.77	.79	.81	.82	.84	.84	.84	.84	.82	.81	.79	Fery thermoelectric 323	3.84
2	.....	.60	.62	.64	.65	.67	.68	.69	.71	.72	.75	.79	.83	.85	.86	Fery thermoelectric 10537	3.53 to 4.55
2	.46	.49	.52	.55	.58	.61	.64	.67	.69	.72	.75	.78	.81	.84	.86	Fery thermoelectric B. S. 30	3.78
2	.51	.53	.55	.56	.58	.59	.61	.63	.66	.71	.77	.83	.86	.87	.88	Fery thermoelectric B. S. 30 with diaphragm	3.90
2	.51	.54	.57	.60	.62	.65	.68	.70	.73	.76	.79	.81	.84	.86	.88	Fery thermoelectric 10530	4.22
2	.59	.60	.61	.62	.64	.65	.66	.68	.70	.74	.79	.83	.85	.87	.88	Fery thermoelectric 10530 with diaphragm	4.26
1	.72	.74	.76	.79	.81	.83	.85	.87	.88	.89	.90	.91	.92	.92	.92	Fery spiral	.....
	.54	.59	.62	.65	.68	.70	.72	.735	.75	.78	.81	.84	.86	.865	.867	Mean	
	.02	.02	.02	.02	.02	.02	.02	.02	.02	.01	.01	.01	.008	.008	.01	Probable error of mean	

Below these are indicated the probable error of the mean. This ranges from $\pm .01$ to $\pm .02$. It can not be claimed, of course, that the actual total emissivity relations of NiO are determined with this accuracy on account of the possibility of some systematic error, but it would appear probable that the correct values are not far different from the above mean values obtained with 12 independent series of observations by pyrometers possessing marked differences in their characteristics as illustrated in the wide variation of the exponent b .

FIG. 9.—Total emissivity vs. temperature

In Fig. 9 are plotted the final observations which definitely establish the increase of the total emissivity of NiO with temperature. Randolph and Overholser, working in the range 200 to 600°, observed a similar increase. In the range 700 to 1200° the present work shows the increase is nearly linear with temperature. Obviously this linear relation will not extend indefinitely, for it can not exceed 1.00 or become zero. The characteristic curve must therefore be S shaped. This departure from the straight line is apparent at 1200 to 1300°. It is possible that the emissivity at still higher temperatures increases very slightly and gradually until the melting of the oxide may bring about a discontinuity in the curve.

Somewhere below 600° the curve must again change its slope, possibly becoming approximately parallel to the axis of temperatures.

TABLE 3
Optical Pyrometer ($\lambda=0.65\mu$) Sighted on Nickel Oxide

Observed temperature	Correction to add	True temperature	Observed temperature	Correction to add	True temperature
°C	°C	°C	°F	°F	°F
700	1	701	1200	1	1201
800	2	802	1400	3	1403
900	4	904	1600	6	1606
1000	7	1007	1800	12	1812
1100	10	1110	2000	18	2018
1200	15	1215	2200	27	2227
1300	20	1320	2400	39	2439

The three points represented in Fig. 9 by circles are from the data of Randolph and Overholser. It is possible to extend our curve so that it will coincide with the 400 and 200° points determined by these investigators. The disagreement of the two curves at 600, however, would indicate a systematic difference between the two sets of data.

TABLE 4
Total Radiation Pyrometer Sighted on Nickel Oxide

Observed temperature	Correction to add	True temperature	Observed temperature	Correction to add	True temperature
°C	°C	°C	°F	°F	°F
500	120	620	900	220	1120
550	115	665	1000	205	1205
600	110	710	1100	195	1295
650	105	755	1200	185	1385
700	100	800	1300	180	1480
750	95	845	1400	170	1570
800	95	895	1500	165	1665
850	90	940	1600	155	1755
900	85	985	1700	150	1850
950	80	1030	1800	135	1935
1000	75	1075	1900	125	2025
1050	70	1120	2000	115	2115
1100	65	1165	2100	105	2205
1150	60	1210	2200	95	2295
1200	55	1255	2300	95	2395
1250	50	1300			

Fig. 10 represents the corrections in degrees centigrade which must be added to the temperature observed with a total radiation pyrometer sighted on NiO in order to obtain true temperatures. On account of the rapid increase of the emissivity with temperature these corrections decrease up to the apparent temperature 1250°. Above this range they probably increase, since here the rate of increase of emissivity with temperature is small.

FIG. 10.—Corrections to total radiation pyrometer

In Fig. 11 are plotted the number of watts per cm² radiated by NiO at various temperatures. For comparison, a similar curve for a black body is given computed from the equation $J = \sigma(T^4 - T_0^4)$ where $\sigma = 5.7 \times 10^{-12}$ watts cm⁻² deg⁻⁴ and $T_0 = 300^\circ$.

Table 4 shows the numerical values of the corrections to be applied to the observed temperatures, both Fahrenheit and centigrade scale, and the corresponding true temperatures for use with any type of total radiation pyrometer.

SUMMARY.—The monochromatic emissivity or absorptivity of nickel oxide (NiO) has been measured for the temperature interval 700 to 1300°C, and its dispersion has been observed spectrophotometrically from $\lambda=0.5$ to 0.7μ for four temperatures in this range.

The monochromatic emissivity increases linearly with increasing wave length throughout the visible spectrum and decreases linearly with temperature from 700 to 1300°C.

FIG. 11.—Radiation loss from NiO and from a black body

Determinations of the emissivity for $\lambda=0.65\mu$ with an optical pyrometer by the method of microscopic melts agreed with the spectrophotometric determinations by the Mendenhall wedge method.

The total radiation of nickel oxide has been studied by use of 12 receivers sufficiently "black" for the requirements of this experiment.

The total emissivity increases with temperature in the interval 600 to 1300° C.

Correction curves and tables are given for use with optical pyrometers of the Wanner, Scimatco, Morse, Le Chatelier, Féry Absorption, Shore, and Holborn-Kurlbaum type instruments using red light ($\lambda = 0.65\mu$), and for radiation pyrometers of the Féry, Foster, and Thwing types.

In conclusion, the writers desire to thank the Taylor Instrument Cos. of Rochester, the Thwing Instrument Co., and the Brown Instrument Co. of Philadelphia for very generously placing at their disposal several radiation pyrometers. Mention is due Messrs. Kellberg and Sale for assistance in some of the observations.

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