NBS MONOGRAPH 41

Theory and Methods of Optical Pyrometry

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. Research projects are also performed for other government agencies when the work relates to and supplements the basic program of the Bureau or when the Bureau's unique competence is required. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's research are published either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three periodicals available from the Government Printing Office: The Journal of Research, published in four separate sections, presents complete scientific and technical papers; the Technical News Bulletin presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of non-periodical publications: Monographs, Applied Mathematics Series, Handbooks, Miscellaneous Publications, and Technical Notes.

A complete listing of the Bureau's publications can be found in National Bureau of Standards Circular 460, Publications of the National Bureau of Standards, 1901 to June 1947 ($1.25), and the Supplement to National Bureau of Standards Circular 460, July 1947 to June 1957 ($1.50), and Miscellaneous Publication 240, July 1957 to June 1960 (Includes Titles of Papers Published in Outside Journals 1950 to 1959) ($2.25); available from the Superintendent of Documents, Government Printing Office, Washington 25, D.C.

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Theory and Methods of Optical Pyrometry

H. J. Kostkowski and R. D. Lee

National Bureau of Standards Monograph 41

Issued March 1, 1962

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C. - Price 25 cents

Contents

Theory and Methods of Optical Pyrometry*

H. J. Kostkowski and R. D. Lee

A detailed review of the theoretical methods of optical pyrometry and the application of these methods at the National Bureau of Standards in realizing, maintaining and distributing the International Practical Temperature Scale above 1063 °C is presented. In the theoretical presentation, the concepts of effective and mean effective wavelengths are introduced, and various equations relating these parameters to each other and other physical quantities are derived. The important features of precision visual optical pyrometers are discussed and a number of blackbody sources and tungsten strip lamps described. Detailed experimental procedures and results of primary and secondary calibrations of optical pyrometers at NBS are given. Finally, recommendations for achieving high precision and accuracy and the fundamental limitations in visual optical pyrometry are presented.

Introduction

The quantity and quality of technical and scientific investigations using optical pyrometry have been increasing steadily during the past 5 years. This has resulted in the need for an improvement in the efficiency and accuracy of optical pyrometer measurements. The National Bureau of Standards (NBS) has tried to meet its responsibilities in this area by developing new instruments such as the photoelectric pyrometer [1] [1] and by re-evaluating the theory and methods of optical pyrometry.

The current paper is an attempt to make the theory of optical pyrometry and the application of this theory at NBS readily accessible. Most of the theory presented is not new or original with the authors. However, much of it is scattered throughout the technical literature, and to the best of our knowledge, a detailed review of the theory in English does not exist. In addition to the general theory of optical pyrometry, the current paper presents the instrumentation and methods currently used at NBS to realize the International Practical Temperature Scale [2] above 1063 °C and to transfer this scale to instruments submitted for calibration.

No attempt has been made to present a complete bibliography on optical pyrometry. References to other papers are given only when a more detailed account than is given here is thought to be helpful to the reader.

1. Theory

1.1. The Planck Radiation Equation

The measurement of temperature utilizing optical pyrometry is based on the fact that the spectral radiance [3] from an incandescent body is a function of temperature. In particular, if the body is black, i.e. can absorb all the radiation that might be incident on it, the Planck radiation equation

$$N_{b\lambda}=\frac{C_1\lambda^{-5}/\pi}{e^{C_2/\lambda T}-1} \qquad (1\text{–}1)$$

relates the spectral radiance to the temperature. In eq (1–1) $N_{b\lambda}$ is the spectral radiance at the wavelength λ of a blackbody at a thermodynamic temperature T, and C_1 and C_2 are the first and second radiation constants. Thus it is possible to determine the thermodynamic temperature of a blackbody through the measurement of $N_{b\lambda}$ provided the other parameters in eq (1–1) are known. Absolute measurements of radiation, however, are very tedious and usually not very precise. To overcome these obstacles one could measure $N_{b\lambda}$ relative to some standard spectral radiance; thus defining a temperature scale based on the ratio of two spectral radiances, one of which is selected as a standard. This is the procedure adopted in the International Practical Temperature Scale (IPTS).

1.2. The International Practical Temperature Scale

The International Practical Temperature Scale of 1948 [2] defines the temperature, t, above the temperature of equilibrium between solid and liquid gold (gold point), t_{Au}, by the equation

$$\frac{N_{b\lambda}(t)}{N_{b\lambda}(t_{\mathrm{Au}})}=\frac{e^{\frac{C_2}{\lambda(t_{\mathrm{Au}}+T_0)}}-1}{e^{\frac{C_2}{\lambda(t+T_0)}}-1} \qquad (1\text{–}2)$$

where C_2 and the gold point, t_{Au}, are defined to be 1.438 centimeter degrees and 1063 °C, respectively,

*This paper was presented at the Fourth Symposium on Temperature, Its Measurement and Control in Science and Industry; Columbus, Ohio; March 27–31, 1961; sponsored by the American Institute of Physics, the Instrument Society of America, and the National Bureau of Standards. The proceedings will be published in book form by the Reinhold Publishing Corporation, New York, N.Y.

[1] Figures in brackets indicate the literature references at the end of this Monograph.

[2] Prior to 1960, this scale was called the International Temperature Scale. The new name, International Practical Temperature Scale, was adopted in October 1960 by the Eleventh General Conference on Weights and Measures.

[3] Spectral radiance is defined as the energy radiated by a body in a particular direction per unit time, per unit wavelength, per unit projected area of the body and per unit solid angle. Radiance is the integral with respect to wavelength of the spectral radiance. The American Standards Association has adopted the symbol, N_λ, for spectral radiance and this notation will be adhered to in this paper. The text of the International Practical Temperature Scale, however, utilizes the symbol J.

and T_0 is 273.15 degrees. Temperature-measuring instruments calibrated at the National Bureau of Standards are calibrated in terms of the IPTS, and therefore, temperature calibrations above the gold point are based on eq (1–2).

If it were possible to use eq (1–2) directly, little more would be required concerning the basic theory of optical pyrometry. However, this cannot be done because any observable radiation consists of a finite spectral band, and the question arises as to the wavelength to use in eq (1–2). In fact, most instruments used for this purpose at the present time use the eye as a detector and require a large spectral bandwidth [4] in order to have sufficient energy for the eye to see. Thus a major part of the theory to be presented is concerned with determining the wavelength to be used in eq (1–2). Since it is simpler to discuss this in terms of a particular instrument, the main features of the instrument commonly used will be given at this time. Nevertheless, the presentation will be sufficiently general to apply with minor modification to any such instrument, visual or photoelectric.

The instrument that is usually used to realize the IPTS above the gold point is the disappearing filament optical pyrometer. A schematic diagram of this instrument is shown in figure 1. The instrument is operated by imaging the blackbody or source whose temperature is to be determined onto the filament of the small pyrometer lamp and varying the current in this lamp until its filament disappears into the background of the source. At this time the photometric brightness [5] of the body and the pyrometer lamp filament as seen through the optical pyrometer are the same.

[4] Photoelectric instruments which are now being developed have smalle- bandwidths but still sufficiently large for the wavelength question to be sig1 nificant.

[5] Photometric brightness of a surface is the radiance of the surface evaluated according to its capacity to produce visual sensation. In this paper, as elsewhere, the adjective photometric will often be omitted. The term luminance is also used sometimes in place of the term photometric brightness.

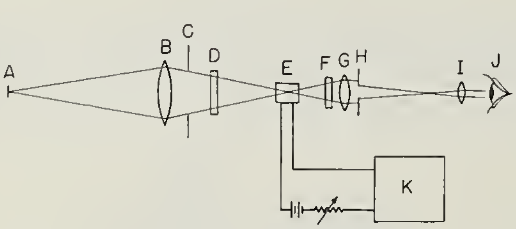


Figure 1. *Schematic diagram of an optical pyrometer.*

If the instrument has been calibrated and the source is a blackbody, this brightness match will result in a temperature determination on the IPTS. The calibration of an optical pyrometer in which an attempt is made to realize the IPTS directly rather than from a calibrated pyrometer or source is termed a primary calibration. The remainder of this section will describe the theory required in order to perform a primary calibration on an optical pyrometer.

1.3. The Primary Calibration at the Gold Point

The first step in the primary calibration of an optical pyrometer is a brightness match of a blackbody at the gold point. A mathematical description of this match, i.e., the brightness of the blackbody being equal to the brightness of the pyrometer lamp, as seen through the instrument, is given by

$$\int_0^\infty N_{b\lambda}(t_{\mathrm{Au}})\tau'_\lambda \tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda = \int_0^\infty N_\lambda(t_1)\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda \quad (1\text{–}3)$$

where $N_{b\lambda}(t_{\mathrm{Au}})$ is the spectral radiance of the blackbody at the temperature t_{Au}, the gold point, τ'_λ is the spectral transmittance of all the optical components preceding the pyrometer filament, $\tau_{r\lambda}$ that of the red filter, τ''_λ that of all optical components following the pyrometer filament except the red glass, V_λ the relative luminosity factor of the observer [6,7] and $N_\lambda(t_1)$ [8] is the spectral radiance of the pyrometer lamp filament at temperature t_1. $N_{b\lambda}(t_{\mathrm{Au}})$ as well as typical curves for V_λ and $\tau_{r\lambda}$ are shown in figure 2. The transmittances τ'_λ and τ''_λ are usually constant and equal to about 0.8 and 0.7, respectively, in the wavelength range of interest. The spectral brightness of a gold-point blackbody, $\beta_\lambda(t_{\mathrm{Au}})$, as seen through such a typical optical pyrometer, is also shown in figure 2. The area under β_λ is equal to the brightness and to the integrals in eq (1–3). When the brightness match is made, measurement of the current in the pyrometer lamp realizes the primary calibration at the gold point. It should be emphasized that the temperature of the pyrometer lamp t_1 or the lamp current at the match depends on the particular transmittances and the observer's relative luminosity factor. Changing any of these will, in general, change the calibration.

1.4. The Primary Calibration Above the Gold Point

To perform a primary calibration above the gold point, a procedure similar to that at the gold

[6] The relative luminosity factor at a particular wavelength or relative visibility function, as it is sometimes called, is the ratio of the luminous flux at that wavelength to the maximum luminous flux, maximum with respect to wavelength.

[7] K. S. Gibson and E. P. T. Tyndall, Visibility of radiant energy, BS Sci. Pap., No. 475 (1923).

[8] Since $N_\lambda(t_1)$ is, in general, a function of direction or angle with respect to the tungsten filament surface, $N_\lambda(t_1)$ in eq (1–3) is an average over the range of angles involved. However, it will be seen later that only $N_{b\lambda}$ will be used quantitatively, and this is independent of direction.

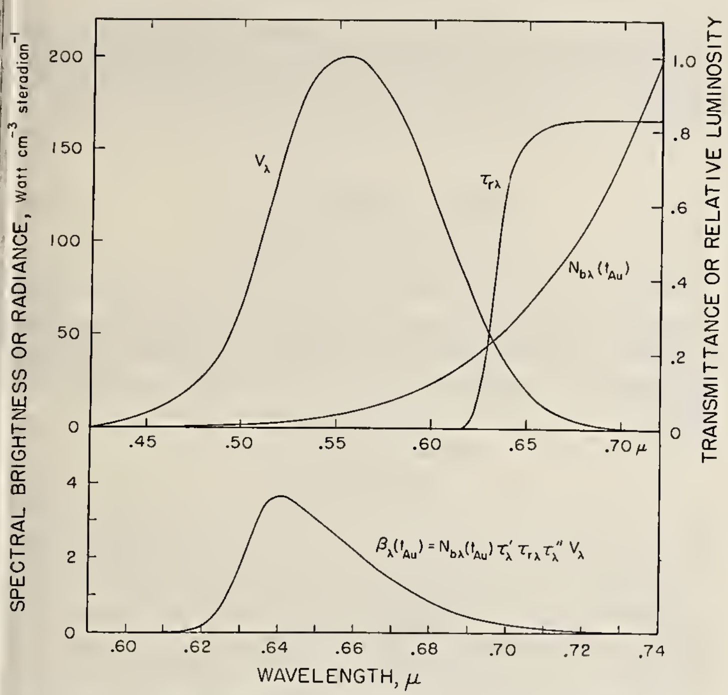


FIGURE 2. *The spectral brightness of a gold-point blackbody $\beta_\lambda(t_{Au})$ as observed by an observer with a relative luminosity function V_λ through an optical pyrometer having spectral transmittances $\tau_{r\lambda}$ for the red glass and $\tau'_\lambda=0.8$ and $\tau''_\lambda=0.7$ for all the optical elements preceding and following the pyrometer lamp filament respectively, excluding the red glass.*

point is followed except that the higher temperature, say t, must be determined. To obtain the temperature t a brightness match is made on the blackbody as seen through a device whose transmittance is constant with wavelength and of such value as to require the same pyrometer filament current as that used in the gold point blackbody match. Mathematically,

$$\int_0^\infty RN_{b\lambda}(t)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda\,d\lambda=\int_0^\infty R\beta_\lambda(t)d\lambda$$

$$=\int_0^\infty N_\lambda(t_1)\tau_{r\lambda}\tau''_\lambda V_\lambda\,d\lambda=\int_0^\infty N_{b\lambda}(t_{Au})\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda\,d\lambda$$

$$=\int_0^\infty \beta_\lambda(t_{Au})d\lambda \qquad (1\text{–}4)$$

where R is the constant transmittance as a function of wavelength of the device, say a sectored disk. From the nature of the various functions in the integrands, a plot of the spectral brightnesses ($_\lambda\beta t$) and $\beta_\lambda(t_{Au})$ together with $R\beta_\lambda(t)$ as a function of wavelength would result in curves similar to those shown in figure 3. The wavelength at which $\beta_\lambda(t_{Au})$ and $R\beta_\lambda(t)$ are equal is called the mean effective wavelength between the temperature t_{Au} and t and is denoted by $\lambda_{t_{Au}-t}$. At this wavelength

$$RN_{b\lambda_{t_{Au}-t}}(t)=N_{b\lambda_{t_{Au}-t}}(t_{Au}). \qquad (1\text{–}5)$$

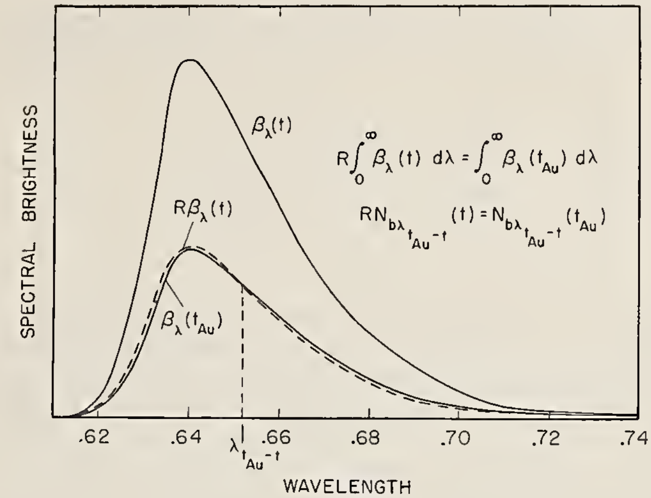


FIGURE 3. *Approximate spectral brightness as observed through an optical pyrometer of a blackbody at the temperature t_{Au} and a blackbody of temperature t such that the brightness of the t_{Au} blackbody equals that of the t blackbody when the latter is observed through a sectored disk of transmittance R.*

$\lambda_{t_{Au}-t}$ is the mean effective wavelength between the temperature t_{Au} and t.

Thus the desired blackbody temperature t satisfies the defining equation for the IPTS and can be obtained by solving (usually numerical solutions are necessary) the integral equation represented by the first and fourth integrals in eq (1–4), provided all the transmittances and the relative luminosity function are known. In this manner a primary calibration could be performed at a temperature t greater than the gold point and repeated (with different sectored disks) for as many temperatures as necessary in order to obtain a smooth curve of blackbody temperature versus pyrometer-lamp current.

1.5. Absorbing Glasses

In order to have a very stable pyrometer lamp a vacuum lamp is usually used.[9] However, to assure long-term stability, a tungsten vacuum lamp is usually not used above a brightness temperature[10] of about 1350 °C. Thus, using the method just described, an optical pyrometer could only be calibrated to about 1350 °C. Higher temperature calibrations could be attained, however, by using the sectored disks as part of the calibrated instrument. For example, a 2280 °C blackbody appears, as seen through a sectored disk having a transmittance of 0.7 percent, to have the brightness at 6500 A of a 1350 °C blackbody. Therefore an optical pyrometer calibrated from

[9] This is discussed in detail in section 2 of this paper.
[10] The brightness temperature of a source is defined as the temperature of a blackbody which has the same spectral radiance at a particular wavelength as the source. Mathematically if $N_{\lambda'}(t)=N_{b\lambda'}(t')$, t' is the brightness temperature of the source at the wavelength λ'. Generally, the brightness temperature is different for different wavelengths.

1063 to 1350 °C together with sectored disks can be used to measure temperatures higher than 1350 °C. Equation (1–4) would be used to determine this higher temperature t where t_{Au} in eq (1–4) is replaced with a temperature below 1350 °C already realized. There are two disadvantages, however, in doing this. One is the inconvenience of using sectored disks routinely. The other is that one cannot realize temperatures much higher than the 2280 °C without incurring large errors from the uncertainty of the sectored disk transmittance. Though it might be possible to design and construct sectored disks for which the angular opening of the disk can be determined to better than 1 min of arc, this has not yet been done. For a 0.007 transmittance which is necessary to achieve 2280 °C an uncertainty of 1 min of arc amounts to an uncertainty of 2.0 deg C.

A means out of this dilemma is the use of a filter rather than a sectored disk to reduce the brightness of the source. Such a filter is called an absorbing glass and is usually inserted between the objective lens and the pyrometer lamp. The primary calibration of the pyrometer for temperature ranges using an absorbing glass would proceed as follows. The temperature t of a blackbody above 1350 °C but below 2280 °C would be determined as described in the last paragraph. Next the sectored disk would be removed, the absorbing glass inserted, and a brightness match made. The current in the pyrometer lamp at the match together with the absorbing glass constitutes a calibration point at the temperature t. Now one is able to proceed to even higher temperatures than 2280 °C because with each absorbing glass one can again use a sectored disk and need not use a disk with a very small transmittance.

There are other advantages in using an absorbing glass, particularly if its spectral transmittance is given by

$$\tau_{a\lambda}=e^{-k/\lambda} \tag{1–6}$$

where k is a constant with respect to wavelength. Suppose t_3 is a blackbody temperature above 1350 °C obtained by using eq (1–4). Looking at such a blackbody without a sectored disk but through an absorbing glass, and using Wien's radiation equation [11] rather than Planck's equation, we have for the integrated brightness

$$\int_0^\infty C_1\lambda^{-5}e^{-C_2/\lambda T_3}e^{-k/\lambda}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$
$$=\int_0^\infty C_1\lambda^{-5}e^{-\frac{C_2}{\lambda}\left(\frac{1}{T_3}+\frac{k}{C_2}\right)}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda \tag{1–7}$$

[11] Wien's radiation equation states $N_{b\lambda}=(C_1\lambda^{-5}/\pi)\exp(-C_2/\lambda T)$ and for a temperature of 5000 °K and a wavelength of 7500 A (approximately the longest wavelength required in eq (1–4)) it is about 2 percent smaller than the Planck equation, while at 2500 °K and 7500 A it is only 0.05 percent smaller.

where $T_3=t_3+273.15$.[12] Thus a blackbody at the temperature T_3 appears through the absorbing glass as another blackbody at a temperature T_2 where

$$\frac{1}{T_2}=\frac{1}{T_3}+\frac{k}{C_2}=\frac{1}{T_3}+A. \tag{1–8}$$

Since k/C_2, the so-called "A" value of the absorbing glass, is a constant, any blackbody whose temperature is T_i will appear through the absorbing glass as another blackbody at a lower temperature T_j where

$$\frac{1}{T_j}=\frac{1}{T_i}+A. \tag{1–9}$$

The apparent temperature T_j can always be made less than 1350 °C by making the A value sufficiently large. Thus with an absorbing glass with this type transmittance, the A value is a constant and once obtained can be used together with eq (1–9) and a lower range calibration to calibrate the upper range. In addition, such an absorbing glass insures a close color match between the pyrometer lamp and the source. This is helpful for precise brightness matching. Furthermore, from eqs (1–7) and (1–8), the A value of two or more absorbing glasses used together is the sum of the individual A values. Therefore, since the A values are also independent of the blackbody temperature, a high-temperature calibration can be obtained without actually making observations at the high temperature but simply by determining the individual A values at some low temperature and adding them together for the high temperature.

1.6. The Relation Between Effective and Mean Effective Wavelengths

The basic principles involved in the primary calibration of an optical pyrometer at any temperature above the gold point have been described. In this method, sectored disks and absorption filters are used, and eq (1–4) is solved numerically for any pair of temperatures represented by t and t_{Au}. However, the amount of tedious calculation can be greatly reduced by introducing and utilizing the concept of effective wavelength.

If Wien's radiation equation rather than Planck's equation is used and t_{Au} and t are generalized to any two temperatures t_1 and t_2, one obtains by using eqs (1–4) and (1–5)

$$\frac{\int_0^\infty \lambda^{-5}e^{-C_2/\lambda T_1}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda}{\int_0^\infty \lambda^{-5}e^{-C_2/\lambda T_2}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda}=e^{-\frac{C_2}{\lambda_{T_1-T_2}}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \tag{1–10}$$

[12] $T_i=t_i+273.15$ °C is called the International Practical Kelvin temperature.

Designating the integrals in the numerator and denominator of eq (1–10) as B_1 and B_2, respectively, and taking the natural logarithm of both sides of eq (1–10) leads to

$$\frac{1}{\lambda_{T_1-T_2}}=\frac{\ln B_1-\ln B_2}{C_2\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}. \qquad (1\text{–}11)$$

The effective wavelength λ_T[13] at $T_1=T$ is defined as

$$\frac{1}{\lambda_T}=\lim_{T_2\rightarrow T}\frac{1}{\lambda_{T-T_2}}. \qquad (1\text{–}12)$$

Through the use of this definition and eq (1–11) one obtains

$$\frac{1}{\lambda_T}=\frac{1}{C_2}\frac{d(\ln B)}{d\left(\frac{1}{T}\right)} \qquad (1\text{–}13)$$

or

$$\int_{\frac{1}{T_1}}^{\frac{1}{T_2}}\frac{1}{\lambda_T}d\left(\frac{1}{T}\right)=\frac{\ln B_2-\ln B_1}{C_2} \qquad (1\text{–}14)$$

and if eq (1–11) is substituted into eq (1–14)

$$\frac{1}{\lambda_{T_1-T_2}}=\frac{1}{\frac{1}{T_1}-\frac{1}{T_2}}\int_{\frac{1}{T_1}}^{\frac{1}{T_2}}\frac{1}{\lambda_T}d\left(\frac{1}{T}\right). \qquad (1\text{–}15)$$

Hence the reciprocal of the mean effective wavelength between two temperatures is the center of gravity of the reciprocal of the effective wavelength with respect to and between the reciprocal temperatures

An expression useful for computing the reciprocal effective wavelength can be derived as follows. From eq (1–10) and the definition of β and mean effective wavelength, one obtains

$$\frac{B_2}{B}=\left(\frac{\beta_2}{\beta}\right)_{\lambda_{T-T_2}}. \qquad (1\text{–}16)$$

Then

$$\left(\frac{B-B_2}{T-T_2}\right)\frac{1}{B}=\left[\left(\frac{\beta-\beta_2}{T-T_2}\right)\frac{1}{\beta}\right]_{\lambda_{T-T_2}} \qquad (1\text{–}17)$$

and

$$\lim_{T_2\rightarrow T}\left(\frac{B-B_2}{T-T_2}\right)\frac{1}{B}=\lim_{T_2\rightarrow T}\left[\left(\frac{\beta-\beta_2}{T-T_2}\right)\frac{1}{\beta}\right]_{\lambda_{T-T_2}} \qquad (1\text{–}18)$$

or

$$\frac{1}{B}\frac{dB}{dT}=\left(\frac{1}{\beta}\frac{d\beta}{dT}\right)_{\lambda_T}. \qquad (1\text{–}19)$$

[13] In some references, the effective wavelength is called the limiting effective wavelength and the mean effective wavelength is called the effective wavelength.

Substituting for β and B, differentiating and solving for $1/\lambda_T$ leads to

$$\frac{1}{\lambda_T}=\frac{\int_0^\infty\frac{N_{\lambda b}(T)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda}{\lambda}d\lambda}{\int_0^\infty N_{\lambda b}(T)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda}. \qquad (1\text{–}20)$$

By numerical integration of eq (1–20), the effective wavelength can be determined for any temperature T. Doing this for 5 or 6 temperatures in a particular range of a pyrometer is usually sufficient to enable one to plot an accurate curve of λ_T versus T for that range. Moreover, it turns out that $1/\lambda_T$ is, to a good approximation, a linear function of $1/T$ and therefore

$$\frac{1}{\lambda_{T_1-T_2}}\simeq\frac{1}{2}\left(\frac{1}{\lambda_{T_1}}+\frac{1}{\lambda_{T_2}}\right). \qquad (1\text{–}21)$$

This approximation is usually correct to about five significant figures. Therefore from the λ_T versus T or $1/\lambda_T$ versus $1/T$ curves and eq (1–21), the mean effective wavelength between any two temperatures can be obtained. When one of the temperatures is not known initially, such as in a primary calibration, the mean effective wavelength is assumed to be 0.65 μ and the unknown temperature computed from eq (1–5). Using this first approximation of the temperature, a second approximation of the mean effective wavelength can be determined from the effective wavelength curve and eq (1–21) and a second approximation of the temperature obtained from eq (1–5). One or two such successive approximations are usually sufficient. Hence, through the use of effective wavelengths, integral equations need be solved only when initially determining the effective wavelength versus temperature curves.

1.7. The Use of Non-blackbody Sources in a Primary Calibration

All that has been presented so far has required a blackbody source, not only at the gold point but at higher temperatures. However, it is possible to use any stable source (excluding, of course, the gold-point blackbody) without error, when absorbing glasses are not used, and a tungsten strip lamp with only small errors ($<1°$), when absorbing glasses are used. This is easily verified from the integrated brightness equations. For example, suppose instead of looking at a blackbody of temperature t_1 through a sectored disk of such transmittance that the blackbody's integrated brightness appeared to be equal to that of a gold-point blackbody, a tungsten strip lamp was used and adjusted until through the same sectored disk, it matched the gold point. Mathematically,

$$\int_0^\infty N_{b\lambda}(t_{\mathrm{Au}})\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$
$$=R\int_0^\infty N_{b\lambda}(t_1)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$
$$=R\int_0^\infty \epsilon_\lambda(t_2)N_{b\lambda}(t_2)\tau_\lambda\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$
$$=R\epsilon_c(t_2)\tau_e\int_0^\infty N_{b\lambda}(t_2^c)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda \qquad (1\text{–}22)$$

where t_2 is the temperature of the tungsten, $\epsilon_\lambda(t_2)$ its spectral emittance, τ_λ and τ_e the spectral and effective transmittance of the glass envelope of the tungsten lamp, $\epsilon_c(t_2)$ is the color emissivity [14] and t_2^c is the color temperature [14] for tungsten at a temperature t_2. From the second and fourth integrals in eq (1–22) and the definition of mean effective wavelength, one notes that the tungsten as seen through the lamp envelope has a brightness temperature [10] t_1 at the mean effective wavelength $\lambda_{t_1-t_2^c}$. If an absorbing glass is inserted in the optical path of the pyrometer when the sectored disk is removed, this mean effective wavelength changes. Mathematically,

$$\int_0^\infty \epsilon_\lambda(t_2)\, N_{b\lambda}(t_2)\tau_\lambda\tau_{a\lambda}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda\, V_\lambda d\lambda$$
$$=\epsilon_c(t_2)\tau_e\int_0^\infty N_{b\lambda}(t_2^c)\tau_{a\lambda}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda\, V_\lambda d\lambda$$
$$=\int_0^\infty N_{b\lambda}(t'_1)\tau_{a\lambda}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda. \qquad (1\text{–}23)$$

In addition as seen from eq (1–23) the brightness temperature will, in general, also change from t_1 to some temperature t'_1. A relationship between t'_1 and t_1 can be obtained as follows. From eqs (1–22) and (1–23) and the definition of mean effective wavelength, one obtains

$$\left[\frac{N_{b\lambda}(t_1)}{N_{b\lambda}(t_2^c)}\right]_{\lambda_{t_1-t_2^c}}=\epsilon_c(t_2)\tau_e=\left[\frac{N_{b\lambda}(t'_1)}{N_{b\lambda}(t_2^c)}\right]_{\lambda_{t'_1-t_2^c}} \qquad (1\text{–}24)$$

Then, using Wien's equation

$$e^{-\frac{C_2}{\lambda_{t_1-t_2^c}}\left(\frac{1}{T_1}-\frac{1}{T_2^c}\right)}=e^{-\frac{C_2}{\lambda_{t'_1-t_2^c}}\left(\frac{1}{T'_1}-\frac{1}{T_2^c}\right)} \qquad (1\text{–}25)$$

and

$$\frac{1}{\lambda_{t_1-t_2^c}}\left(\frac{1}{T_1}-\frac{1}{T_2^c}\right)=\frac{1}{\lambda_{t'_1-t_2^c}}\left(\frac{1}{T'_1}-\frac{1}{T_2^c}\right). \qquad (1\text{–}26)$$

[14] The color temperature of a source in a particular wavelength region is here defined as that temperature at which a blackbody has in this spectral region the same relative spectral radiance as the source. Mathematically, $\epsilon_\lambda(t)N_{b\lambda}(t)=\epsilon_c(t)N_{b\lambda}(t^c)$ for all wavelengths where ϵ_c is the color emissivity and a constant with respect to wavelength.

Rearranging and subtracting $1/T_1\lambda_{t'_1-t_2^c}$ from each side of eq (1–26) gives

$$\frac{1}{T_1}\left(\frac{1}{\lambda_{t_1-t_2^c}}-\frac{1}{\lambda_{t'_1-t_2^c}}\right)=\frac{1}{T_2^c}\left(\frac{1}{\lambda_{t_1-t_2^c}}-\frac{1}{\lambda_{t'_1-t_2^c}}\right)+\frac{1}{\lambda_{t'_1-t_2^c}}\left(\frac{1}{T'_1}-\frac{1}{T_1}\right). \qquad (1\text{–}27)$$

Combining the term on the left of eq (1–27) and the first term on the right, multiplying through by $\lambda_{t'_1-t_2^c}$, and solving for $1/T'_1$ results in

$$\frac{1}{T'_1}=\frac{\lambda_{t'_1-t_2^c}-\lambda_{t_1-t_2^c}}{\lambda_{t_1-t_2^c}}\left(\frac{1}{T_1}-\frac{1}{T_2^c}\right)+\frac{1}{T_1}. \qquad (1\text{–}28)$$

In practice T'_1, the brightness temperature with the absorbing glass inserted, is only a degree or two different from T_1 and very insensitive to T_2^c. The correction of a degree or two can usually be made sufficiently accurate so that the resulting error is less than one degree.

It has been shown that a blackbody source is not needed for a primary calibration above the gold point of an optical pyrometer. When absorbing glasses are used, however, a source for which a color temperature exists, at least in the spectral bandwidth of the pyrometer, and which is approximately known as a function of brightness temperature is required.

The basic theory of optical pyrometry has been developed. The application of this theory at NBS to actual calibrations of optical pyrometers is given in sections 4 and 5. The basic characteristics of optical pyrometers and the sources of radiation commonly used in optical pyrometry will be presented in sections 2 and 3.

2. Optical Pyrometers

In this section, some of the more important general characteristics of optical pyrometers as well as a detailed description of the NBS pyrometer will be presented. Detailed accounts of the commercially available instruments are given in instruction manuals issued by the manufacturers or, for the noncommercial instruments, in published research papers [3–6].

2.1. General Characteristics of Optical Pyrometers

The visual optical pyrometer, the schematic diagram of which is shown in figure 1, is an instrument of surprisingly high precision and accuracy. This is mainly the result of the high stability of the pyrometer lamp and the proper selection of apertures and filters.

a. The Pyrometer Lamp

The pyrometer lamp is probably the most important element in the optical pyrometer. It serves as the instrument's reference standard for radiance. Most pyrometer lamps used today consist of a round or flat highly pure tungsten filament in an evacuated small (dimensions of a few centimeters) glass envelope. The envelope has plane windows of good optical quality which are sometimes oriented so as to avoid troublesome reflections. A vacuum rather than gas lamp is preferred because the elimination of convective and reduction of conductive heat transfer make the lamp's radiance less dependent on its orientation or ambient temperature [5].

Typical dimensions of lamp filaments are 0.03 to 0.05 mm diameter for round filaments and 0.05 to 0.1 mm by 0.005 mm for ribbon filaments. Lengths vary from 20 to about 40 mm. The small cross-sectional area and relatively long length keep the current and voltage requirements low (30 to 200 ma, which is obtained with less than 6 v) and reduce the heat losses through lead conduction, thus further reducing the effect of ambient temperature on lamp radiance. These filament dimensions also make the time constant of the lamp short. For example, pyrometer lamps of the type described reach within 2 deg C of their final temperature within 5 to 60 sec from the initial turn-on time, the exact time depending on the particular filament dimensions and the final temperature.

Pyrometer lamps are usually calibrated using electrical current as the parameter to which the brightness temperature is related. Current is a more convenient parameter to use than lamp resistance or power input and appears to be a sufficiently stable function of brightness temperature, at least to the extent of requirements in visual optical pyrometry. Direct current is used so that a potentiometer may be utilized for determining the current. It is important that the direction of current in the filament during use be the same as that for which the lamp was calibrated. Due to the Thompson effect, a reversal of the current will modify the temperature distribution along the filament and therefore change the radiance at the sighting area. Most commercial pyrometer lamps have a rate of change of current with brightness temperature varying from about 0.05 ma per degree at 800 °C to 0.1 ma per degree at 1350 °C. Corresponding figures for higher source temperatures when using absorbing glasses can be determined by using eq (1–9).

New pyrometer lamps are extensively annealed or aged before being calibrated. The purpose of the annealing is to complete the recrystallization of the tungsten which occurs when the metal is subjected to high temperature. Since the recrystallization modifies the resistivity and emittance of the tungsten, the calibration of the pyrometer lamp will change during this time. Usually, the lamps in commercial pyrometers are annealed by the manufacturer. For lamps made at NBS, an anneal of several thousand hours at about 1800 °K (approximately 1400 °C brightness temperature at 0.65 μ) has been adequate for visual optical pyrometry. However, recently, using the new NBS photoelectric pyrometer [1] several NBS and commercial lamps were observed to change in brightness temperature (for a fixed current) from ½ to 1 °C in 300 hr in the vicinity of 1063 °C after having been annealed for 2000 hr at 1800 °K. On the other hand, one NBS constructed pyrometer lamp has been used for about 4000 hr without changing this much. At the present time, the difference in the two results is not understood. Thus, unless the stability of a particular pyrometer lamp has been established, it is recommended that for accurate work a lamp be compared with other lamps or recalibrated after being used for 200 hr. As a corollary to this, an optical pyrometer lamp after being calibrated should be left off except when brightness matches are actually being made, keeping in mind of course the time required for the lamp to reach equilibrium.

b. Apertures and Filters

In addition to the stability of the pyrometer lamp, two characteristics which are required for an accurate optical pyrometer are that the ratio of the brightness of the pyrometer filament to that of the source be independent of the source distance and that there be a highly reproducible means for realizing this ratio.

The first characteristic is largely achieved through the microscope and objective apertures. The microscope aperture is the aperture stop for the entire optical system, and from a geometrical optics viewpoint is adequate to maintain the ratio of the source to the filament brightness independent of source distance. However, due to the diffraction pattern of the source being partially obscured by the filament, the radiance of the source image, particularly in the vicinity of the pyrometer filament, depends on the angular size of the cone of radiation incident on the pyrometer filament. By adding the objective aperture, this cone is kept constant regardless of source distance.

In most optical pyrometers, the test that the observer uses to determine the existence of the brightness ratio or match is the disappearance of the pyrometer filament into the source image. For this to occur the color of the incandescent filament must be (visually) the same as that of the source image. For temperatures below which absorbing glasses are used, this is achieved fairly well by using a sharp cut-off red filter with a transmittance curve such as that shown in figure 2. This filter, cutting off the shorter wavelengths, and the visibility function of the eye, cutting off the longer wavelengths, produce a sufficiently narrow spectral bandwidth so that an adequate color match exists for most sources. However, Lovejoy has shown [7] that greater precision can be obtained for brightness temperatures below 850 °C by removing the red glass. This is a consequence of increasing the apparent brightness of the source and the pyrometer filament and therefore decreasing the eye's threshold contrast or contrast limen.[15]

Where sector disks or neutral absorbing glasses are used or where a non-blackbody source has a much higher color temperature than its brightness temperature, a noticeable color mismatch may exist. The spectral distribution of the source is characteristic of a high temperature while that of the filament of a low temperature, giving the source image a more orange like color relative to the filament. An observer will probably be aware of a difficulty in brightness matching or disappearance before he is aware of the color mismatch. This effect is minimized, at least for blackbody and tungsten sources, by the use of absorbing glasses which have the previously described exponential transmittance. Most high-precision optical pyrometers use such absorbing glasses.

c. Fairchild's Criterion

Even when a color match exists, a complete visual disappearance is not possible in some optical pyrometers. As a brightness match or disappearance is approached, a thin dark line appears outside the edge of the filament, and/or a bright line appears inside the edge. The origin of these lines has not been definitely established. However, Cunnold [8] develops a rather strong case that the bright line is caused by deviations from Lambert's cosine law, particularly for round filaments, and that the dark line is caused by diffraction effects at the edge of the pyrometer filament. Fairchild and Hoover [3] experimentally determined how to avoid the appearance of these effects and obtain complete visual disappearance. They found that if the ratio of the exit angle to the entrance angle at the pyrometer filament, α/β, as shown in figure 4 is sufficiently small, the dark or bright lines are not observed. The required ratio for disappearance is a function of the width and shape (round or flat) of the pyrometer filament [3] and has become known as Fairchild's criterion. It should be pointed out, however, that Cunnold [8] contends that complete disappearance is not the most precise condition for determining a brightness match and that the apertures can be selected such that the resulting enhanced variation of brightness across a round filament permits a more precise match than can be obtained by disappearance. Moreover, under these conditions, the exit angle may be made considerably larger and since the pyrometer's transmittance is greater, lower brightness temperatures can be measured or a narrower spectral bandwidth can be used. The latter would allow a more accurate determination of mean effective wavelength. In spite of Cunnold's convincing arguments, little effort has been made in this direction, and complete disappearance is still used to determine a brightness match in most visual optical pyrometers.

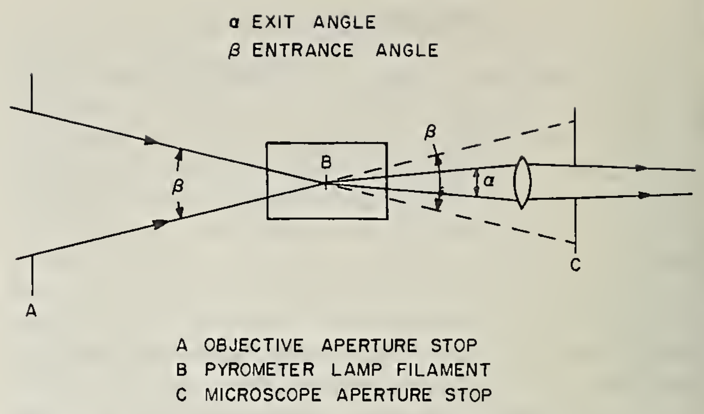


Figure 4. *Schematic diagram showing the entrance and exit angles at the optical pyrometer filament.*

Optical pyrometer design has not been carried to its ultimate but only to the extent that the major limitation in precision and accuracy is the observer. The more important general characteristics and requirements of this design have been presented. Their integration into an actual instrument will be illustrated through a detailed description of the NBS optical pyrometer.

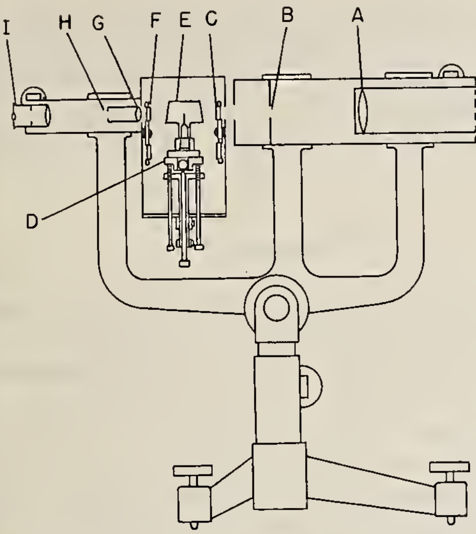
2.2. The NBS Optical Pyrometer

The National Bureau of Standards maintains a specially designed visual optical pyrometer for realizing the International Practical Temperature Scale above 1063 °C and for distributing this scale throughout the United States by the calibration of pyrometers and tungsten strip lamps. The NBS pyrometer is based on the design of Fairchild and Hoover [3] and, to the best of our knowledge, has been in use since about 1923. It is described here in order to clarify the pyrometer design characteristics already discussed and to prepare the reader for sections 4 and 5 on calibrations.

a. Objective Lens Assembly

Figure 5 is a cross section of the NBS optical pyrometer. The objective lens is a plano-convex achromatic doublet with a clear aperture of 4.3 cm and a focal length of about 13.6 cm. The source is generally positioned about 65 cm from the pyrometer filament and the objective lens adjusted through a rack and pinion gear assembly until the source image is at the filament. At this position the objective lens is about 45 cm from the source and 20 cm from the source image. The objective aperture is 1 cm in diameter and 10.8 cm from the filament, forming a fixed entrance angle of about 0.093 radian, independent of the position of the objective lens.

[15] Contrast limen is defined as $|(B_t - B_s)/B_s|$ where B_s is the brightness of a background reference source and B_t is the brightness of a test area for which there is a 50 percent probability of an observer's detecting it from the background. The contrast limen is a function of B_s and increases rapidly for brightness lower than those associated with optical pyrometer observations below about 1000 °C.



A OBJECTIVE LENS
B OBJECTIVE APERTURE
C ABSORBING GLASSES
D ADJUSTABLE LAMP MOUNT
E PYROMETER LAMP
F RED FILTER
G MICROSCOPE OBJECTIVE LENS
H MICROSCOPE APERTURE (Aperture stop)
I HUYGENS OCULAR

FIGURE 5. *Sketch of the NBS visual optical pyrometer.*

In the construction of the NBS pyrometer, provision was made for inserting sectored disks between the objective aperture and the pyrometer lamp. Though this position is still used occasionally for routine work, it is no longer used in primary calibrations because of vibrations being set up in the pyrometer filament and because of the sectored disks of low transmittance acting as objective apertures. The alternate position for the sectored disks that is usually used is at the source. This is accomplished by forming with an auxiliary lens an image of the source at the distance from the filament that the source itself is normally positioned and placing the sectored disk there.

b. Absorbing Glasses, Pyrometer Lamp and Red Filter

The absorbing glasses, pyrometer lamp, and red filter are contained in a box in which the temperature can be accurately controlled. Thermostating this box, however, was found unnecessary and has not been done for years. Nevertheless, as a precautionary measure, the temperature of the room in which the pyrometer is used is controlled to within ±1.5 deg C.

The absorbing glasses are mounted on a disk which can be rotated into any of four positions representing four of the instrument's five ranges. These are designated as Ag 0 (no absorbing glass), AG 1, AG 2, and AG 3, and are used for temperatures from 800 to 1350 °C, 1300 to 1750 °C, 1700 to 2050 °C, and 2000 to 2400 °C, respectively. Their spectral transmittances are given in table 1. The fifth range is selected by placing another absorption glass called the extension glass in front of the objective lens and using it in series with AG 3. The instrument can be used up to 4000 °C in this manner. AG 1 and the extension glass are Corning pyrometer brown glasses and have a constant *A* value at least within the precision of the measurements. Ag 2 and 3 are composite glasses. Before the advent of the Corning pyrometer brown glass, a constant *A* value was achieved by combining two or more glass filters. Only the red portion of the spectrum needed to be considered, and these glasses appear magenta to the unaided eye.

The pyrometer lamp is mechanically mounted with sufficient degrees of freedom to permit precise alinement. The lamp, now in use, is designated L1 and has been used in the pyrometer since 1953. It is a vacuum lamp with a round filament 0.035 mm in diameter and about 40 mm long. The filament contains a number of small coils which increase the length of the filament possible and decrease the effect of ambient temperature. The coils also reduce temperature gradients by radiation exchange. The central part of the filament is horizontal except for a slight dip at the center which serves to indicate the portion used in brightness matches. The lamp envelope is Pyrex and has plane windows inclined about 10 deg from the normal to the optical axis as shown in figure 5.

The previous gold-point primary calibrations of L1 indicate that it has not changed by more than 1.5 deg C at 1063 °C since 1953 and has not changed at all within the experimental error since 1957.

Following the pyrometer lamp in the optical train is the red glass whose spectral transmittance is given in table 1. It is located 4.0 cm from the pyrometer filament and is mounted on a rotatable disk similar to that containing the absorbing glasses. The disk has open areas in which red glasses from optical pyrometers being calibrated may be mounted and compared to the NBS red glass.

TABLE 1. *Spectral transmittances of the absorbing glasses and the red filter in the NBS visual optical pyrometer and the CIE standard relative luminosity factors*

Wave-length	Spectral transmittances				Luminosity factors (CIE)
	Ag 1	Ag 2	Ag 3	Red filter	
mμ					
600	0.043	0.009	0.003	0.000	0.631
610	.048	.010	.003	.001	.503
620	.052	.011	.004	.019	.381
630	.056	.011	.004	.292	.265
640	.059	.012	.005	.678	.175
650	.062	.014	.005	.800	.107
660	.065	.015	.006	.830	.061
670	.067	.017	.006	.841	.032
680	.069	.019	.007	.847	.017
690	.070	.022	.009	.850	.0082
700	.070	.025	.010	.850	.0041
710	.070	.028	.011	.849	.0021
720	.070	.031	.012	.846	.00105
730	.069	.034	.014	.844	.00052
740	.068	.037	.015	.839	.00025
750	.066	.040	.017	.836	.00012
760	.065	.044	.018	.830	.00006
770	.063	.048	.020	.826	.00003
780	.060	.051	.022	.821	.000015

c. Microscope Assembly

Beyond the red glass is a lens assembly similar in design to a low-power microscope. The objective lens of the microscope is 0.7 cm in diameter, has a focal length of about 4.0 cm and is mounted about 6.3 cm from the pyrometer filament. At a distance of 4.0 cm from the microscope objective is the microscope aperture which is the aperture stop for the entire pyrometer. For brightness temperatures above 1050 °C, the aperture stop is 0.16 cm in diameter, producing an exit angle at the pyrometer lamp of about 0.04 radian. This, in conjunction with the 0.093-radian entrance angle, satisfies Fairchild's criterion for visual disappearance for the round filament used. At brightness temperatures between 950 and 1050 °C an aperture stop of 0.24 cm is used, from 850 to 950 °C an aperture stop of 0.32 cm is used and below 850 °C a stop of 0.40 om is used. With these larger stops Fairchild's criterion is not satisfied, being sacrificed in order to increase the apparent brightness [16] and reduce the contrast limen. However, the apparent brightness is now low enough so that the edge effects are not visible to the eye, i.e., disappearance still exists.

A 10-power Huygens ocular completes the microscope assembly and the optics of the optical pyrometer. The microscope assembly thus magnifies the pyrometer filament by a factor of about 17, and since the source observed by the pyrometer objective is magnified by 0.5, the overall magnification of the source by the pyrometer is about 8.5. With the 0.16 cm aperture stop, the exit pupil, which is the image of the aperture stop formed by the ocular, is about 0.07 cm. When compared to the eye pupil diameter of 0.3 to 0.5 cm for the brightness encountered with this aperture stop, one is led to postulate that disappearance of the pyrometer filament is achieved to some extent by insufficient resolving power, fine details at the edge of the filament being washed out.

d. The Electrical Circuit

The electrical current measuring apparatus used with the NBS pyrometer is rather straightforward. The pyrometer lamp is connected in series with a resistance box, a multiturn rheostat, a 6v lead storage battery, a milliammeter, and a 0.1-ohm standard resistor. A high-precision potentiometer, standardized by a temperature stabilized saturated electrical cell, determines the filament current by measuring the voltage drop across the 0.1-ohm standard resistor.

The L1 current ranging from 65 to 160 ma is usually determined to the nearest 0.01 ma. Values of current corresponding to 1 deg C change in brightness temperature are 0.12 ma at 800 °C, 0.17 ma at 1063 °C, and 0.20 ma at 1350 °C. It has been a relatively simple matter, using the above described electrical equipment, to attain a long-term reproducibility in pyrometer lamp current measurements of better than 1 part in 10,000 which is more than adequate for visual optical pyrometry.

[16] The apparent brightness is proportional to the retinal illumination and the exit pupil of the pyrometer is generally smaller than the pupil of the eye. Therefore by increasing the aperture stop diameter, the illumination and the apparent brightness can be increased.

3. Sources

The two major types of sources used in optical pyrometry are blackbodies and tungsten strip lamps. The blackbody is the most fundamental source of radiation because it is generally accepted that the Planck radiation equation exactly describes the spectral radiation from a blackbody as a function of temperature and wavelength. However, highly stable blackbodies are not convenient to use, particularly at high temperatures. Moreover, blackbodies for temperatures much higher than 1000 °C are not readily available commercially (as of 1961). On the other hand, tungsten strip lamps are highly stable, easy to use, and commercially available. As a result, when very accurate knowledge of the spectral distribution of radiation from a source is not as important as high stability and convenience, tungsten strip lamps are used.

In this section some of the general principles of the design and use of blackbodies, tungsten strip lamps, and other sources will be presented, with particular emphasis on those used at NBS.

3.1. Blackbodies

A blackbody is a substance or object which completely absorbs any radiation that is incident on it. If such a substance or object has a uniform temperature, it will emit radiation as determined by its temperature and by Planck's radiation equation. Lampblack is an example of a substance that approaches a blackbody, at least in the visible spectral region,[17] to within about 1 percent, i.e., it absorbs about 99 percent of the visible radiation falling on it.

A hollow, opaque body containing a small hole can be made to approximate a blackbody extremely well, and sources used as blackbodies are usually of this type. In such bodies, the smaller the area of the hole relative to the area of the walls of the cavity, the higher the emittance or blacker the body. For a particular geometry, the blackness of a hollow body also depends on the reflectivity of the inner surface of the cavity, including how diffuse or specular it is. As an

[17] It is possible for a substance or object to have an absorptance of unity in some wavelength region or regions but not in all. Such a body is not, strictly speaking, a blackbody; but radiates as a blackbody in the regions where its absorptance is unity. From Kirchoff's law, which states that the ratio of the spectral radiance of a body at a uniform temperature to its spectral absorptance is equal to the spectral radiance of a blackbody, and from the definition of spectral emittance given in section 1, the spectral absorptance of a body is equal to its spectral emittance.

example, the radiation emitted from the bottom of a hollow cylinder of which one end is closed and the other open and whose inner walls are at a uniform temperature is about 0.99 that of a blackbody provided the ratio of the depth of the cylinder to its radius is 10, its normal reflectivity is 0.2, and it is diffuse [9]. If the same conditions existed except for the reflectivity being largely specular, the effective emittance of the cylinder would be about 0.90 [9]. Calculations of the effective emittance of hollow bodies of various shapes, sizes, and reflectivities can be found in the literature [9–11].

a. Gold-Point Blackbodies

The hollow bodies used as gold-point blackbodies for realizing the IPTS are probably the closest approximation to blackbody radiators currently in existence. Figures 6 and 7 show two such "blackbodies,"[18] with vertical and horizontal axes respectively, which were designed and constructed at NBS. The gold used to surround the cavities is 0.99999 pure. In both cases the sighting tubes and the crucibles for the gold are made of the highest purity graphite available so that

[18] For convenience, a hollow body used to approximate a blackbody will be referred to as a "blackbody."

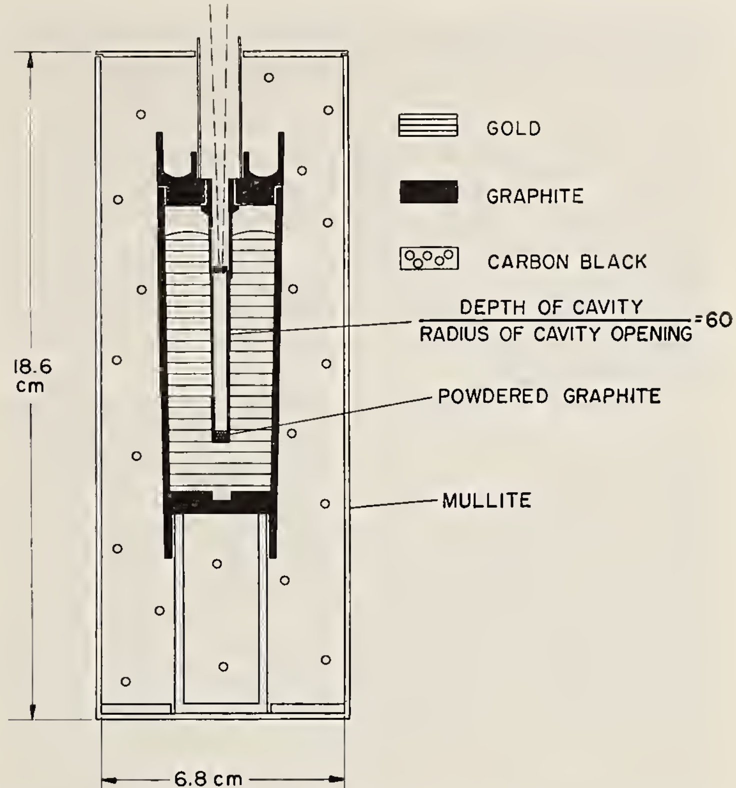


FIGURE 6. *Cross section of the NBS vertical gold-point blackbody.*

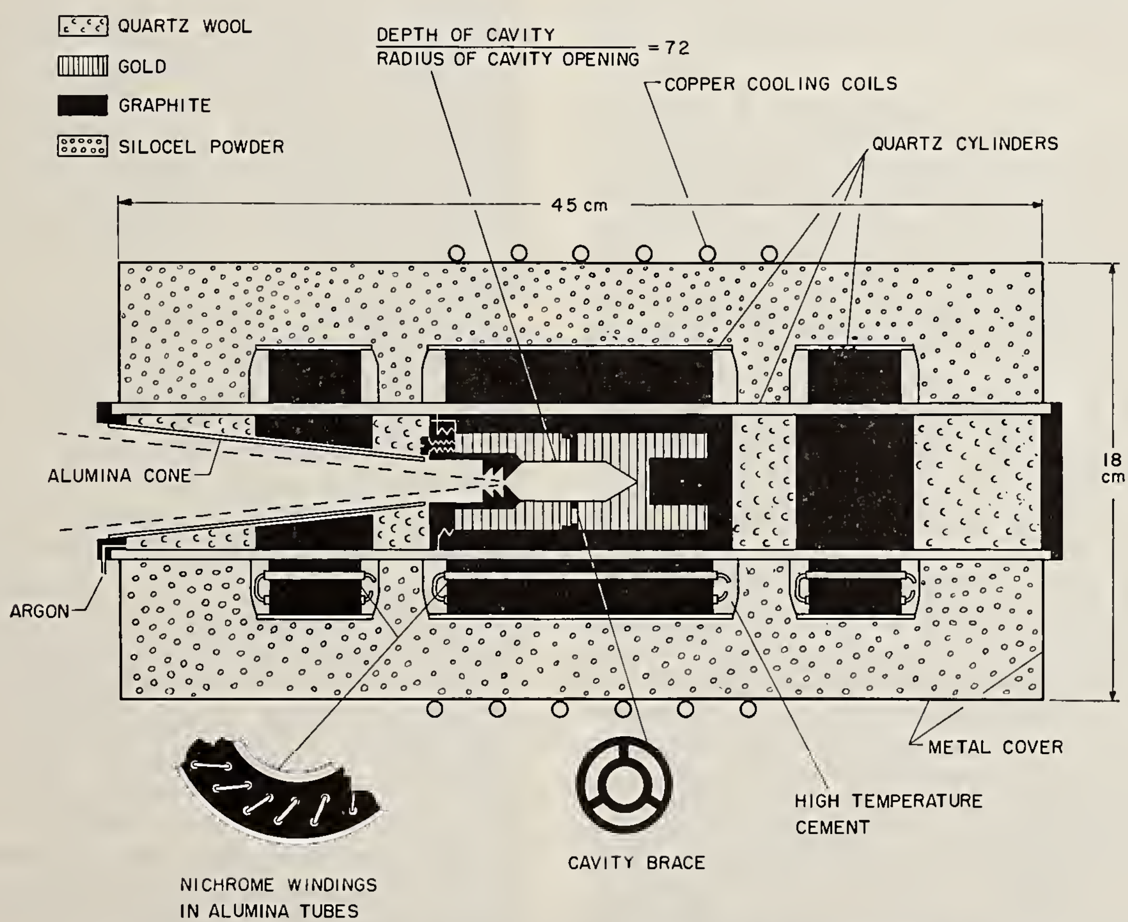


FIGURE 7. *Cross section of the NBS horizontal gold-point blackbody and furnace.*

the gold remains uncontaminated. The graphite used is reported by the manufacturer to contain impurities not exceeding 20 parts per million. In addition, the graphite has a high emittance, a fairly high thermal conductivity, and is easy to machine. The latter factor has made possible the construction of sight tubes of ¼-mm wall thickness for the vertical "blackbody" and ½ mm for the horizontal type. The thinner the walls and the higher their thermal conductivity, the closer the inside temperature of the walls will be to that of the freezing gold.

The vertical "blackbody" assembly is heated in a wire-wound muffle furnace or in the coils of an RF generator. It is estimated, using the calculations of Gouffé [11] that the emittance of the vertical "blackbody," assuming the walls are at a uniform temperature, is 0.999. A partial confirmation of this emittance was obtained experimentally in the following manner. The region above the diaphragm in the sight tube (see fig. 6) itself approximates a blackbody, but of lesser quality than the main "blackbody." The depth of this "blackbody" is somewhat greater than the height of the gold above the diaphragm and its base is the diaphragm of the primary enclosure. Optical pyrometer measurements made on this base during a gold-point freeze resulted in a brightness temperature 0.6 °C less than that obtained from the primary enclosure. A calculation of the relative emittance of these two "blackbodies" is compatible with the 0.6 °C observed, and increases one's confidence in the estimate of the emittance of the main sight tube.

Though the vertical "blackbody" is easier to construct, its use required that the axis of the optical pyrometer be vertical or that a reflector be used in conjunction with the "blackbody." For many years, a 45-degree prism was used at NBS for this purpose. Its A value was determined sufficiently well so that it introduced an uncertainty of the gold-point radiance of no more than the equivalent of 0.1 or 0.2 °C. However, in order to avoid this additional uncertainty and in order to have as black a "blackbody" as possible to be used with the recently developed NBS photoelectric pyrometer, the horizontal "blackbody" and furnace shown in figure 7 were developed.

In the design of the horizontal "blackbody" and furnace, attention was placed on achieving a uniform temperature over the inner walls of the sight tube. The crucible containing the gold is shaped so that the mass of gold per unit length of the crucible is about constant for the crucible's entire length. The furnace has three independently controlled heater windings which are embedded longitudinally in cylindrical graphite muffles. The graphite, having a high thermal conductivity, tends to reduce longitudinal temperature gradients. The power inputs to the two end windings are adjusted to maintain the two end sections at 1063 °C as determined by two thermocouples positioned near the inner surface of these sections. The center winding is used to control the rate of heat loss by the gold during a freeze. With this design, it is expected that the gold will freeze more uniformly over the entire sight tube than in the vertical blackbody.

It has not been possible to detect in gold-point freezes differences between the vertical and horizontal "blackbodies" using a visual optical pyrometer. Such differences that may exist are so small they will require the photoelectric pyrometer for detection. The detailed results of using these gold point "blackbodies" will be given in the Primary Calibration section.

b. Lesser Quality "Blackbodies"

Lesser quality "blackbodies," particularly at temperatures much higher than the gold point, are required occasionally in optical pyrometer calibrations.[19] In addition, they are preferred for accurate spectral calibrations of monochromators and spectrographs. One such "blackbody" that has been used at NBS up to temperatures of 3000 °C consists of a graphite cylindrical tube resistively heated in an argon atmosphere and surrounded by a number of graphite radiation shields. The tube is about 200 mm long, has a wall thickness of about 3 mm, and an inside diameter of about 9 mm. A small hole in the center of the tube and correspondingly larger holes in the shields permit the radiation to exit. A current of about 800 amp is required to reach a temperature of 2800 °C. The tube can be used for about 50 hr at this temperature and the radiance stabilized for several hours to better than 1 percent by automatically controlling the current in the tube. The effective emittance of this "blackbody" is currently (1961) being investigated.

"Blackbodies" are sometimes built into an experimental apparatus so that the temperature in an experiment can be determined with an optical pyrometer. For example, to determine the surface temperature of an incandescent material whose spectral emittance at 0.65 μ is not known, a small hole could be made in the material and optical pyrometer observations made on this "blackbody." The depth to diameter ratio of the hole will usually be a compromise between that required for an adequate absorptance and that insuring a uniform temperature throughout the hole which is equal to the temperature at the surface. In general, even when blackbody conditions cannot be met well, temperature measurements on a poor "blackbody" with estimated corrections often may be more accurate than utilizing the brightness temperature of the surface and a poor estimate of the emittance.

---

[19] Tungsten strip lamps usually are adequate for this purpose, as discussed in section 1, Theory.

3.2. Tungsten Strip Lamps

The most stable lamp currently available is the small vacuum pyrometer lamp described in the Optical Pyrometer section Though excellent as a reference standard in optical pyrometers, its smallness makes this lamp unsuitable for use in checking or calibrating optical pyrometers, or for spectral-radiance calibrations of monochromators or spectrographs. For these purposes a larger type tungsten lamp called a strip or ribbon filament lamp is often used. A variety of these lamps is commercially available from the General Electric Company in the United States (to the best of our knowledge the sole supplier in the U.S.), General Electric Co., Ltd., in England, and Philips' Lamp works in the Netherlands.

a. Types of Strip Lamps

In the United States, the tungsten strip lamp most commonly used for optical pyrometer applications is the General Electric Company type 30A/6V/T24 ribbon filament lamp. The first two numbers in the type designation mean that if 6 v is applied to the lamp, the resulting current is about 30 amp. This lamp has a glass envelope about 75 mm in diameter and 300 mm long and a tungsten ribbon filament about 0.075 mm thick, 3 mm wide, and 50 mm long. In order to increase the reproducibility of observing the same point or area of the filament, the filament is notched on one edge at about the midpoint of its length. A V bend toward one end of the ribbon allows it to expand or contract without twisting or bending when its temperature is changed. The envelope contains, according to the manufacturer, argon at a pressure of about ⅓ atm at room temperature. The filament is approximately parallel to the axis of the envelope. Its exact position varies, but it is preferable that the filament be situated off the axis of the envelope and that it be oriented so that the normal to its surface is not on a radius of the cylindrical envelope.[20] There is sufficient volume in the envelope above the filament to allow convective gas currents to flow smoothly upward from the filament and thus allow any tungsten vapor to condense on the upper portion of the relatively cool envelope.

The 30A/6V/T24 lamp requires a current of about 14 amp for a brightness temperature of 1000 °C and about 45 amp for 2300 °C. The change of current per degree change in brightness temperature varies from about 0.010 to 0.030 amp per degree from 800 to 2300 °C, respectively. Direct current is usually used so that standard potentiometric measurement methods can be employed. When a sufficiently high-current source is not available, some of the lower current lamps should be considered. However, their narrower filament makes brightness matching more difficult with optical pyrometers having a low magnification.

A strip lamp that is especially useful when a higher brightness temperature is required is the the General Electric 75A/T24. The filament and filament supports for this lamp are designed to permit the lamp to be used up to a brightness temperature of about 2800 °K. In addition, the lamp may be obtained with a plane quartz window so that it can be used in the ultraviolet spectral region. However. these lamps require about twice the current of the 30A/6V/T24 lamp and have no notch.

The General Electric Co., Ltd., in England manufactures a vacuum tungsten strip lamp which is highly recommended for use below 1400 °C. It is called a secondary standard tungsten strip vacuum pyrometer lamp and requires only about 7 amp to achieve a 1400 °C brightness temperature. This lamp has been used at NBS up to 1750 °C, but if high stability is required, it is recommended that the lamp not be used above about 1400 °C.

The High Temperature Measurements Laboratory at NBS has had very little experience with Phillips' tungsten lamps made in the Netherlands. Lamps made in this country have usually been adequate. However, with the increased stability required of tungsten sources in photoelectric pyrometry, this will probably not continue to be the case and tungsten strip lamps from essentially every source will have to be investigated in the near future.

b. Factors Affecting the Reproducibility of Strip Lamps

There are a number of factors which must be considered in order to obtain the optimum reproducibility and stability with tungsten strip lamps. Many of these have been investigated by Barber [5], DeVos [6], and by the High Temperature Measurements Laboratory at NBS. The following is a brief summary of the factors considered to be of major importance.

Tungsten strip lamps possess a temperature gradient along the length of the strip with a maximum temperature at or near the notch. In T24 type lamps the brightness temperature gradient at the notch may vary from zero to 5 deg C per millimeter, depending on the particular lamp, its temperature, and orientation. The direction of the current also has an effect. The current direction is important because when direct current exists in a region of a temperature gradient, heat is absorbed or generated (in addition to the "Joule heating") depending on the direction of the current relative to the gradient. This is called the Thompson effect; and in tungsten, if the current direction is from hot to cold, heat is absorbed. When the direction is from cold to hot, heat is generated. Thus in order to obtain reproducible brightness temperatures from a strip lamp, care must be taken to sight at the same point or region. This is usually the notch.

[20] Reasons for this will be given later in this section.

Another factor important in obtaining reproducibility with a strip lamp is the room or ambient temperature, particularly for brightness temperatures below 1500 °C for gas-filled lamps and 900 °C for vacuum lamps. The convective and conductive heat losses depend on the ambient temperature, and if the ambient temperature changes, the resulting temperature at the notch will change. For example, Barber [5] observed a variation of brightness temperature of 0.3 deg C per 1 deg C change of ambient temperature for a gas-filled lamp at a brightness temperature of 1050 °C. At the very high filament temperatures, the energy loss from a filament is largely radiative, and the room temperature has much less effect.

The temperature at the notch for gas lamps is also a function of the lamp orientation. This is caused by gas convection currents in the lamps, and Barber [5] shows the effect to be about ½ deg C for a forward tilt of the filament of an angle of 1 deg. At NBS, gas lamp strip filaments are adjusted with the aid of a plumb line to be vertical at the notch.

In general, the radiance or brightness temperature of a tungsten strip lamp depends on the direction of observation. This is due to the fact that the emittance of tungsten is a function of the angle of emission. It is also caused by reflections. Radiation from the filament may be reflected by the envelope onto the tungsten strip and then into the pyrometer's field of view. The emittance variation as a function of angle of emission is very small near normal emission and can usually be neglected. This is not the case for the reflection effect, and it is desirable to orient the lamp with respect to the optical pyrometer to avoid these reflections. Figure 8 shows several examples of the reflection under discussion. It can be seen that the nature of the reflection depends on the position of the filament relative to the axis of the envelope and on the orientation of the plane of the filament. Case *c* is the preferred positioning and orientation of the filament. In this case the filament may be observed normally without any contribution from reflections. It is desirable to view a filament normally because of the small emittance variation stated above. and because at normal emission the radiation will not be polarized. In case *a* when the filament is on the axis of the lamp, it is impossible to avoid reflections. In case *b*, reflections can be avoided but observations must be made off the normal. In using lamps in position *b*, one should keep in mind that the radiation is partially polarized.[21] When lamps are used or calibrated at NBS, the best direction of sighting is decided on, and an arrow is etched on the glass envelope such that a line extending from the head of the arrow through the notch defines the desired direction.

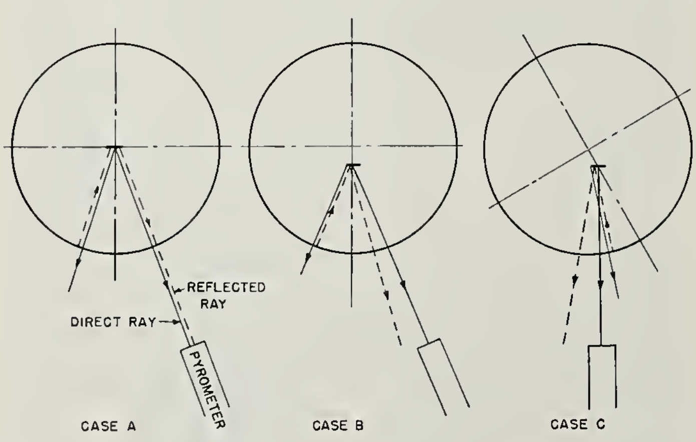


Figure 8. *Examples of reflections in a cylindrical envelope tungsten strip lamp for three different positions and orientations of the strip.*

In order to achieve stability, a tungsten strip lamp should be extensively aged or annealed. Some of the details concerning annealing were discussed previously in connection with the small pyrometer lamps. DeVos [6] claims that after annealing a tungsten strip for 100 hr at 2400 °K, 20 hr at 2600 °K, or 2 hr at 2800 °K, no further change in its radiance (at constant current) was observed.[22] At NBS, gas-filled strip lamps are annealed at between 2325 and 2350 °C brightness temperature (a tungsten temperature of about 2625 °C) for 2 hr. After such an annealing and after taking the necessary precautions with the various factors discussed in this section, 30A/6V/T24 gas lamps have been used as high as 2200 °C for 50 hr and as high as 2380 °C for 20 hr without any change in their radiance being detectable. The precision of these measurements was about 2 deg C. It should be emphasized, however, that all gas-filled strip lamps may not possess this kind of stability; and at present, very little statistical information on their stability is available.

3.3. Other Sources

a. The Carbon Arc

At brightness temperatures higher than about 3000 °C, no convenient, stable sources are at present (1961) available. The positive crater of a carbon arc has been recommended and used as a radiation standard [12–14] at the sublimation temperature of carbon. At this temperature the brightness temperature of the crater corresponds to about 3527 °C at 0.65 μ. However, the carbon arc is not as convenient to use as a lamp and is highly stable only at the one temperature.

b. High-Pressure Arc

At brightness temperatures above 3000 °C, gaseous sources probably are the greatest hope for the future. Xenon high pressure arcs have been

[21] This is probably important only in using strip lamps to calibrate an optical system containing mirrors. Such a system may have a transmittance which depends strongly on the polarization of the radiation.

[22] This presumably means no change within the long-term precision of his measurements which appears to be about 1 percent in spectral radiance.

studied extensively [15] and are available commercially. Their usefulness in optical pyrometry, however, has not yet been established.

4. Primary Calibration

The temperature scale above 1063 °C that is maintained at the National Bureau of Standards is the result of attempting to realize the International Practical Temperature Scale using the methods of optical pyrometry. The experimental attempt to realize any portion of this scale without comparison with previously calibrated pyrometers or sources is called a primary calibration. In the previous sections of this paper, the IPTS above 1063 °C was defined and the theory and instruments used in optical pyrometry described. This section presents the results of the 1958 primary calibration of the NBS visual optical pyrometer.

4.1. Calibration at the Gold Point

The initial step in the primary calibration at the gold point was the optical alinement of the "blackbody" and the pyrometer. The optical axis of the NBS pyrometer was positioned on the axis of the vertical "blackbody," and the pyrometer focused on the "blackbody" diaphragm. The "blackbody" was slowly heated until the gold was melted and brought to a temperature estimated at 5 to 10 deg C above the melting point. It was then allowed to cool, and brightness matches were made as a function of time. The pyrometer lamp current, corresponding to these brightness matches, plotted against time constituted the gold-point "blackbody" cooling curve. As the "blackbody" cooled, its brightness decreased rather rapidly, and then increased slightly. This dip, seen on the typical cooling curve in figure 9, is called the undercool. After the undercool, the brightness remained constant within the reproducibility of the determinations, and matches were made about every 15 sec alternating between a bright pyrometer filament to disappearance and a dark filament to disappearance. The average of two such matches was considered one observation. The brightness remained constant from 5 to 8 min, allowing 10 to 16 observations. This plateau represented the freezing-point temperature of the gold.

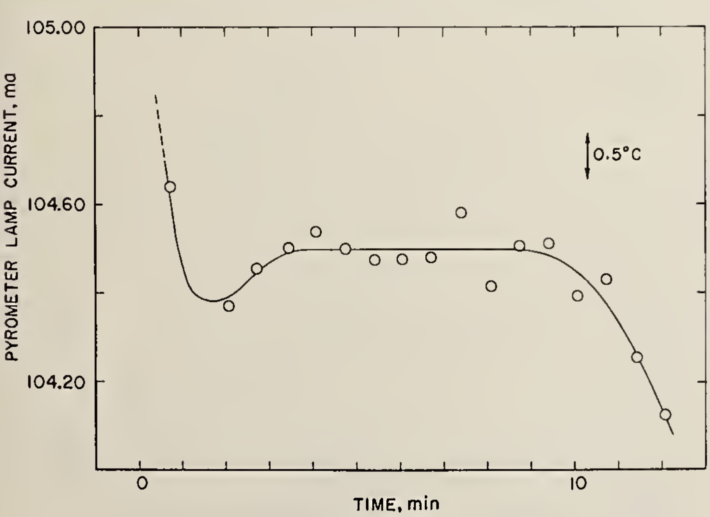


FIGURE 9. *A typical cooling curve obtained during a gold-point calibration with the NBS visual optical pyrometer and the vertical gold-point "blackbody."*

In the primary calibration of 1958, about 50 such plateaus were taken on the vertical "blackbody" over a 2-month period by 3 experienced observers using both an RF generator and a muffle furnace for heating. Though the muffle furnace system had a larger heat capacity and freezes lasted 2 to 3 times longer, the lamp currents corresponding to the plateaus of the cooling curves were the same to better than the standard deviation of an observer's brightness matches, or the equivalent of about 0.2 deg C.

Heating or melting curves were also obtained. When inductively heating, the brightness matches corresponding to the melts were almost 1 deg higher than those obtained during the freezes; but in the muffle furnace, they were only a few tenths of a degree higher.[23] The large difference in the case of the RF melt is attributed to a less uniform heat input and to the background conditions in the pyrometer field of view affecting one's judgment of the match. In the case of freezes, the cooling is more uniform and the brightness of the region which surrounds the small sighting hole or diaphragm is negligibly different from the brightness of the sighting hole. Only the freezes were used for the actual calculation of the gold-point calibration.

The results of the 1958 gold-point determination are given in table 2. In addition, data obtained in 1957 and 1960 are included. The observations in 1957 were made using a vertical "blackbody" similar to that in 1958, but the horizontal "blackbody" of figure 7 was used in 1960. The 1957 and 1958 results include the effect of a 45° right-angle prism and represent a temperature lower than the gold point due to the prism absorption and reflection. This apparent gold-point temperature was calculated from eq (1−9) where $T_t = T_0 + 1063 = 1336.15$ °K and $A = 6.92$ mireds[24] resulting in $T_j = T_{\text{app}} = 1323.9$ °K. The A value of the prism was determined independently using a strip lamp and data from the previous primary calibration. The standard deviation of the A value of each of three observers about their grand mean was equivalent to about 0.1 deg C. Since only relatively small differences of temperature near the gold point were required to determine A, use of the

[23] Observations made in 1960 on the horizontal "blackbody" resulted in melts only 0.1 deg C higher than the freezes.

[24] The unit in which A values are usually reported is the mired. One mired is equal to 10^{-6} (°K)$^{-1}$.

TABLE 2. *NBS primary optical pyrometer calibrations at the gold point using a glass prism and an apparent temperature of 1323.9 °K*

Observer	1957				1958				1960 [a]			
	L1 Pyrometer lamp current [b]	Number of freezes	Standard deviation [c]		L1 Pyrometer lamp current [b]	Number of freezes	Standard deviation [c]		L1 Pyrometer lamp current [b]	Number of freezes	Standard deviation [c]	
			S_1	S_2			S_1	S_2			S_1	S_2
	ma		*ma*	*ma*	*ma*		*ma*	*ma*	*ma*		*ma*	*ma*
RDL	104.465	9	0.023		104.450	17	0.019		104.484	3	0.029	
RCH									104.457	1		
RCG					104.426	16	.036		104.427	2	.028	
HJK									104.410	1		
EL									104.573	2	.018	
ATH					104.522	12	.042					
Mean of all observers	104.465				104.466			0.049	104.470			0.059

[a] The 1960 data were obtained using a horizontal "blackbody," and therefore the glass prism used with the vertical "blackbody" was not required. As a result, for comparison purposes, the 1960 data were normalized to 1323.9 °K.
[b] 0.05 ma is equivalent to 0.3 °C.
[c] S_1 is the sample standard deviation of an individual's freezing point determinations about his own mean. S_2 is the sample standard deviation of individual observers' mean determinations about the mean of the determinations of all observers.

former calibration data did not significantly affect the accuracy of *A*. If no previous calibration had existed, a sectored disk and strip lamp would have been used to determine the *A* value of the prism. The horizontal "blackbody" constructed after 1958 and used in 1960 did not require the use of a prism. For comparison in table 2, the 1960 data were adjusted to the apparent temperature of 1323.9 °K or 1050.7 °C using the completed calibration.

Table 2 shows that the standard deviation of an individual's single freeze varied from about 0.1 to 0.25 deg C about his own mean. The difference between observers was as large as 1 deg when only a few freezes were taken. Even the means of 16 freezes of RCG and 12 freezes of ATH differed by 0.6 deg C, though the sum of the standard deviation of the two means was about 0.13 deg C. These differences can not be accounted for by relative luminosity factor differences. The differences in the measured relative luminosity factors would account for only about 0.1 deg C. Moreover, the observer differences would be less when using a tungsten strip lamp; but the observers maintained the same differences in this case. When observations were made on tungsten strip lamps through sectored disks with an apparent temperature near the gold point, the same differences still remained. These differences between observers at the gold point were attributed to their matching technique and to psychological factors, and the only way of reducing their effect on the accuracy is to use a number of observers. The observer effect may be indicated quantitatively by the standard deviation of an observer about the mean of all observers. In the 1960 data, where five observers were used, this standard deviation was estimated to be 0.4 deg C.

4.2. Calibration Above the Gold Point

To extend the calibration to temperatures above and below [25] the gold point, tungsten strip lamps were matched through sectored disks and eq (1–5) used to calculate the new temperature *t*. Then the sectored disk was removed and the strip lamp matched to obtain the pyrometer current corresponding to the new temperature. The transmittances, *R*, of the sectored disks were determined in the Metrology Division of NBS and the mean effective wavelength, $\lambda_{t_{Au}-t}$, were obtained from eq (1–21) using the effective wavelengths shown in figure 10. The latter were calculated with eq (1–20) using spectral transmittance functions of the pyrometer elements determined at NBS and the CIE [26] standard relative luminosity factors.[27] However, it was found from independent measurements that the relative luminosity factors of the observers were slightly different from the CIE factors. This produced an average change in the

[25] Even though the International Practical Temperature Scale is defined by Planck's radiation equation only above 1063 °C, optical pyrometers are frequently required at lower temperatures.

[26] Commission Internationale de l'Eclairage.

[27] I.E.S. General Guide to Photometry, Illuminating Engineering Society, New York, N.Y. (1954).

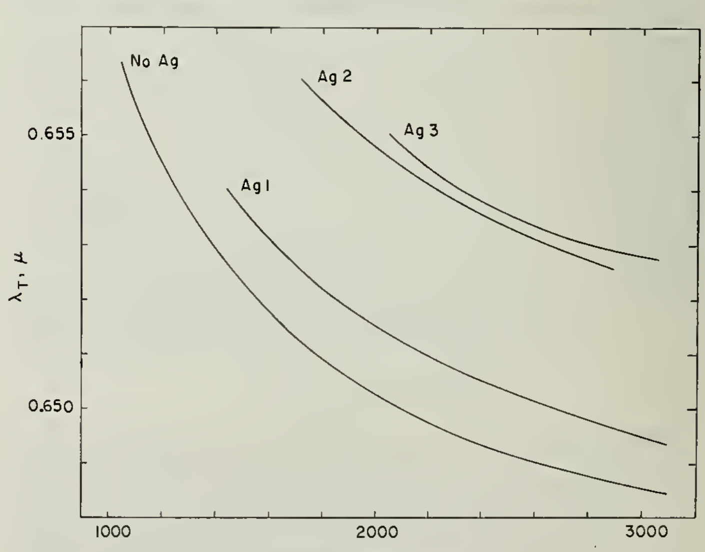


FIGURE 10. *Effective wavelengths for the NBS visual optical pyrometer using the CIE standard relative luminosity factors.*

mean effective wavelengths of about 7 A, and required a correction from about −0.2 deg C at 800 °C to about +3.2 deg C at 2400 °C.

For observations using sectored disks, the disks were positioned at the tungsten-strip image which was produced by a lens corrected for spherical aberration and coma. The strip-lamp current was continually monitored to insure constancy of lamp brightness. Using 7 sectored disks ranging in transmittance from 0.35 to 0.007, three observers made 50 sets of observations for the low range from 800 to 1300 °C, 42 for the range 1300 to 1750 °C using absorbing glass number one (AG 1), and 30 sets each for AG 2 and AG 3 covering 1750 to 2050 °C and 2050 to 2400 °C, respectively. Each set of observations consisted of 4 brightness matches with the sector, 6 without, and 4 more with the sector. Again, matches were made by approaching the disappearance alternately from the dark and bright side. Each observer used his own gold-point or low-range calibration to obtain the apparent temperature.

In the low-range calibration above 1051 °C, the lamp brightness through the sectored disks was maintained close to that of the gold "blackbody" as seen through the glass prism, i.e., 1051 °C. For temperatures less than 1051 °C, the lamp brightness was adjusted to about 1051 °C when not looking through the sector. Figure 11 shows the results of the low-range calibration for the three observers. I_{table} in figure 11 was obtained from the original (1952) calibration for this pyrometer lamp. If a previous calibration had not been available, a 3d- or 4th-order polynomial approximately fitting the new calibration could have been used to obtain an I_{table} as a function of temperature. For the low-range calibration the standard deviation of an observer about his own mean was approximately 0.35 °C.

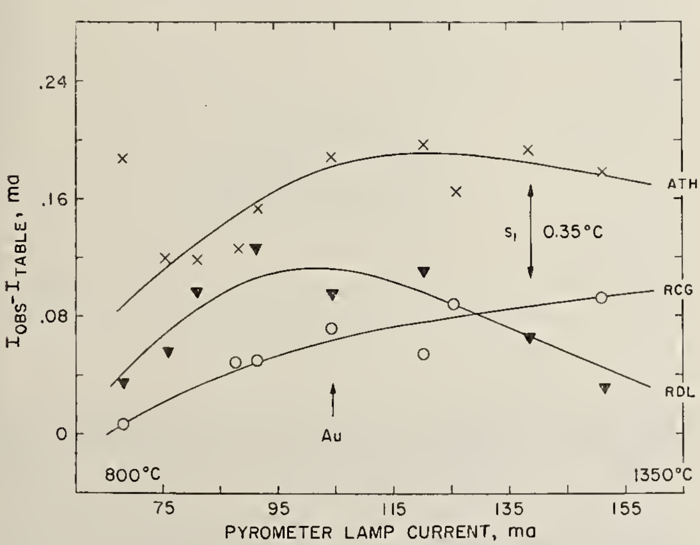


FIGURE 11. *The 1958 primary calibration of the low range of the NBS visual optical pyrometer.*

For the higher ranges where AG 1, 2, and 3 are used, brightness temperatures of the source as seen through the sectored disks were not maintained at the gold point alone, but also at other points already calibrated in the low range. A values were calculated from eq (1–9) for each set of observations where T_i was the apparent temperature as seen through the absorbing glass and T_j the brightness temperature of the strip lamp obtained from a sectored disk calculation. It should be emphasized that the brightness temperature of the tungsten strip lamp T_j must correspond to the mean effective wavelength for the absorbing glass used. Figures 12, 13, and 14 show the A values obtained for each of the absorbing glasses. The standard deviation of an observer's A value about his own mean varied by an equivalent of 1.0 to 2.0 deg C.

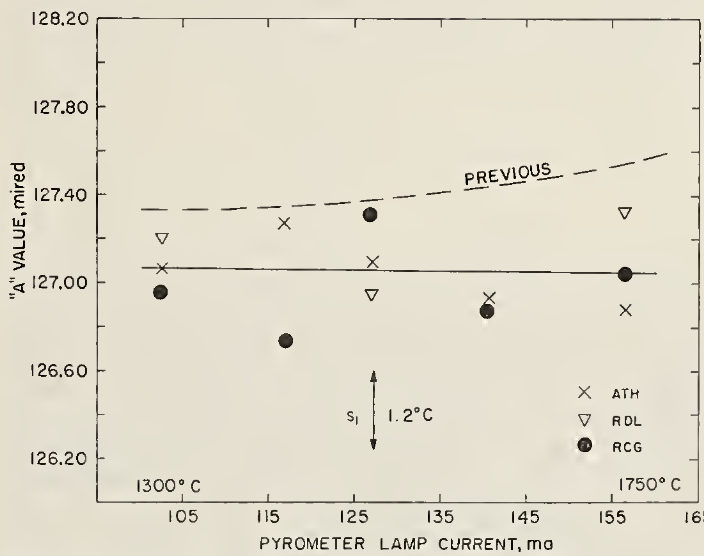


FIGURE 12. *The 1958 determination of the A value of absorbing glass 1 of the NBS visual optical pyrometer.*

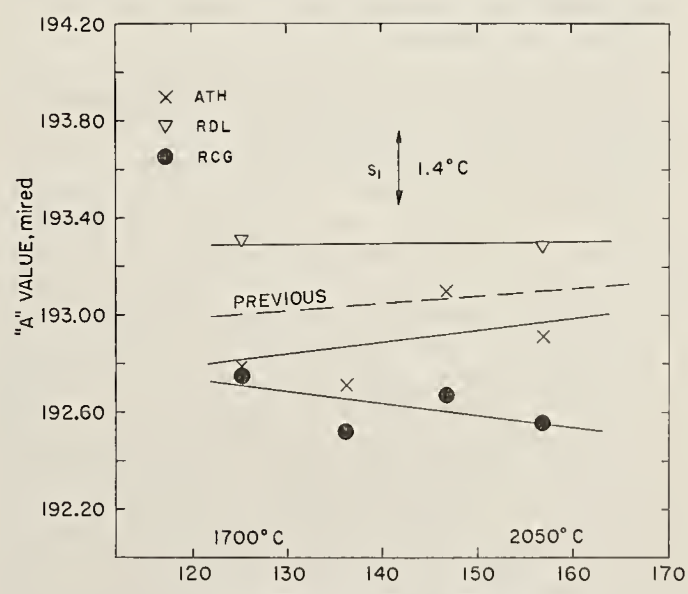


FIGURE 13. *The 1958 determination of the A value of absorbing glass 2 of the NBS visual optical pyrometer.*

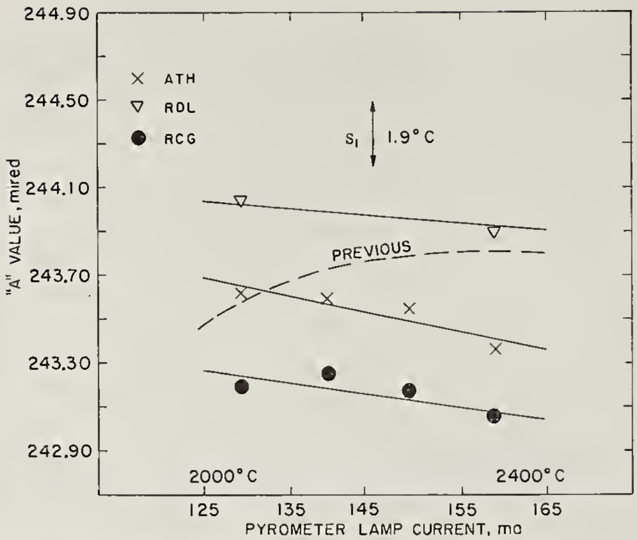


FIGURE 14. *The 1958 determination of the A value of absorbing glass 3 of the NBS visual optical pyrometer.*

An analysis of the data obtained for the low-range calibration reveals that the observers continue to read strip lamps with about the same difference throughout the low range, except for a slight trend of observer RDL indicated by the crossover of his calibration with that of observer RCG. Thus the observer differences throughout the low range also appear to be the result of judgment or psychological factors. Therefore it was decided to take the mean of three observers and apply an average relative luminosity factor correction to the mean. The 1958 low-range calibration, including luminosity corrections, is 0.8 deg C lower than the 1956 calibration at 800 °C and 0.9 °C higher at 1350 °C.

The A values for all the absorbing glasses are, within the experimental error, constant with source temperature, thus supporting an $\exp[-k/\lambda]$ transmittance. Except for AG 1, differences continue to exist between observers that have no adequate explanation. In analyzing the data, it is seen that ATH and RCG have the same differences in temperature when matching with or without sectors, and this is independent of current. However, ATH and RDL match differently through sectors when the apparent temperature is changed. When matching through absorbing glasses, ATH and RDL maintain the same difference that exists between them at the gold point but ATH and RCG change by 0.6 °C. The mean of the A value curves for the three observers was corrected for the average relative luminosity factor of the three observers and used in conjunction with the average low-range calibration to obtain calibrations for the high ranges. The 1958 calibration of the upper ranges is about equal to the 1956 calibration at 1400° C, 0.6 deg higher than the 1956 calibration at 1700 °C, and 2.4 deg C higher at 2000 and 2400 °C. Part of these differences is attributed to the relative luminosity factor corrections which were made in 1958 but not in 1956.

4.3. Estimated Accuracy

An estimate of the accuracy of this primary calibration can be made by comparing it with the mean of similar calibrations from other national laboratories throughout the world. In fact, to the best of our knowledge, this is the only way of quantitatively estimating the accuracy. Fortunately this can be done through the international comparison of strip lamps completed in 1958. Figure 15 shows the difference as a function of temperature between the strip lamp calibration at NBS using six observers and using the 1958 primary calibration and the mean of the strip-lamp calibrations of three other national laboratories. These are the Deutsches Amt für Mass und Gewicht, German Democratic Republic, the National Research Council, Canada, and the Physikalisch-Technische Bundesanstalt, Federal Republic of Germany. The standard deviation of all four national laboratories about their grand mean is also given in figure 15. This serves as an indication of how well the IPTS above 1063 °C has been realized.

It is felt that the results of the 1958 primary calibration at NBS is about the best one can expect from visual optical pyrometry. The major limitations are the sensitivity of the eye to differences in brightness and the knowledge of the mean effective wavelengths.

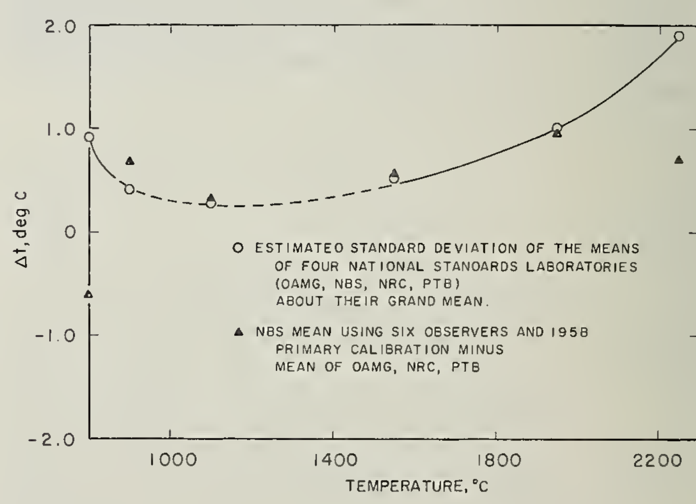


FIGURE 15. *The international comparison of strip lamp calibrations completed in 1958 between Deutsches Amt für Mass und Gewicht (DAMG) of the German Democratic Republic, NBS of the United States, National Research Council (NRC) of Canada, and Physikalisch-Technische Bundesanstalt (PTB) of the Federal Republic of Germany.*

The dashed curve represents a region in which the estimated standard deviations are somewhat less reliable due to the fact that the laboratories rounded off their data to the nearest degree.

5. Secondary Calibrations

The International Practical Temperature Scale that is realized and maintained at the National Bureau of Standards is distributed throughout the United States through the NBS calibration and test services. The fees and instructions for utilizing these services are listed in the Federal Register. The present section describes in detail the procedures used in calibrating optical pyrometers and tungsten strip lamps.

5.1. Optical Pyrometers

a. Inspection and Cleaning

The initial step after receiving an optical pyrometer submitted for calibration is the general inspection of the instrument to confirm that it is in good operating condition. If it passes this test, the optical elements of the instrument are cleaned, using lens tissue and distilled water. The surfaces of the objective lens, absorbing glasses, and the window of the pyrometer lamp, which is located between the source and the pyrometer lamp filament, are the most important surfaces to clean. A reminder is given on optical pyrometer certificates that the optical surfaces should be kept clean in order for the calibration to be applicable.

b. Determination of the Effective Wavelengths

Since optical pyrometers are usually calibrated by comparison with the NBS pyrometer using a tungsten strip lamp and not a blackbody as a transfer source,[28] differences between the mean effective wavelengths of the test and the NBS instrument are required. These differences are used to calculate from eq (1–28) the brightness temperature T_1' that the test pyrometer should indicate when the NBS pyrometer indicates T_1. Even though both instruments are observing the same tungsten lamp, the brightness temperature obtained by the two should be different if their effective wavelengths are different. If a blackbody were used, this would not be the case. Thus $T_1'-T_1$ must be determined as a function of temperature and added as a correction to each brightness temperature determined by the NBS pyrometer during the calibration.

The differences in mean effective wavelengths required for the above temperature corrections are obtained by either of two methods. The first method is to determine the spectral transmittances of the red filter and the absorbing glasses of the test pyrometer and to calculate the effective and mean effective wavelengths as outlined in sections 1 and 4. Effective wavelengths have been determined for the NBS pyrometer for the primary calibration, and therefore differences between mean effective wavelengths for the NBS instrument and the test instrument can be computed. The second method, though simpler to use when established is not quite so straightforward, and therefore a detailed description will be given.

The second method consists of determining the brightness temperatures with the NBS pyrometer using its own red filter and the test pyrometer red filter for a series of sources for which the brightness temperatures are the same when using the NBS red filter but for which the color temperatures vary from values very large compared to the brightness temperature to values close to it. Such sources can be obtained by using a strip lamp in conjunction with a number of sectored disks. With each of the sectored disks the lamp brightness is adjusted so that when observed through the disk, the lamp has the same brightness temperature. Using eq (1–28), the differences between the mean effective wavelengths are calculated. The limit of the mean effective wavelengths for the test red filter as the disks are changed and the color temperature approaches the brightness temperature is the effective wavelength for that red filter at the limiting brightness temperature. This is repeated for a sufficient number of brightness temperatures in the low range, in order to determine by curve fitting the effective wavelength as a function of temperature for the entire range. The resulting wavelengths, however, represent only a first approximation to the effective wavelengths required. The reason is that the calibration of the NBS pyrometer using the test red filter is slightly different from that using its own red filter. A closer approximation can be obtained by correcting the primary calibration of the NBS pyrometer with the first approximation of the effective wavelength for the test red glass. The improved calibration for the NBS pyrometer when using the test red filter will usually modify the temperature differences determined initially for the series of sources by about 25 percent and permit a second approximation to the determination of the test instrument effective wavelength. This second approximation is usually adequate.

Since the spectral transmittance curves of most red filters used in optical pyrometers have the same general shape, their effective wavelength versus temperature curves are approximately parallel. Therefore, usually one effective wavelength determination is sufficient. Moreover, at NBS the actual temperature corrections to be applied to the test pyrometer have been determined as a function of the temperature difference observed using a particular strip-lamp brightness and sectored disk and the uncorrected NBS primary calibration. Such a set of curves need be computed only once and, thereafter, a single observation through each of the two red filters, using one lamp brightness and sectored disk, is

[28] However, a resistively heated graphite tube "blackbody" similar to that described in section 3.2 is being investigated at NBS for use as a transfer source in the calibration of optical pyrometers up to 2800 °C. Using a blackbody would eliminate the need for determining the differences in effective wavelength.

sufficient to determine the correction to be applied at every temperature of the calibration.

For optical pyrometers which have absorbing glasses with a constant A value, the effective wavelengths of the higher ranges are approximately equal to the effective wavelengths of the low range for corresponding pyrometer lamp currents. In these cases the effective wavelengths determined for the low range also suffice for the higher ranges. When the type of absorbing glass used is not of the constant A value type or is not known, effective wavelengths for the higher ranges are calculated from experimentally determined transmittances.

Most of the visual optical pyrometers received for calibration that have been manufactured since about 1959 appear to have mean effective wavelengths negligibly [29] different from those of the NBS instrument. However, this is not the case for the older instruments. Some of these have had differences as large as 0.01μ, corresponding to about a 5 deg C correction at a tungsten brightness temperature of 2400 °C and to about a 1 deg C correction at 1063 °C.

c. Calibration Procedure

After determining the effective wavelength and/or corresponding tungsten brightness temperature correction as a function of temperature for the test optical pyrometer, the test pyrometer is carefully mounted alongside of the NBS instrument so that their optical axes are parallel and in the same horizontal plane. A GE tungsten strip lamp, 30A/6V/T24, is oriented as described in section 3, on a large lathe serving as an optical bench so that it can be easily and accurately translated in a direction perpendicular to the optical axes of the pyrometers. Surplus lathes have been found quite adequate for such purposes. For convenience, micro-switches are positioned on the lathe bed so that the lamp may be stopped exactly on the optical axis of each pyrometer.

The tungsten strip lamp is specially selected to have its filament positioned off the lamp axis, and therefore the filament plane can be made perpendicular to the pyrometer axis without detrimental reflection effects. The brightness temperature of the lamp as a function of distance from the pyrometer is also determined; and, if large, the lamp is not used. As a result of this careful arrangement of the pyrometer and lamp, the orientation of the lamp with respect to each pyrometer is the same within the experimental errors of the alinement.

The test optical pyrometer could be compared to the NBS instrument in the same manner in which it is used; that is, a brightness match made with the test instrument and the scale on this instrument read. However, a different procedure has been found to be more accurate and convenient. The calibration is performed in two parts, the first being a lamp calibration where the brightness temperature indicated by the instrument is determined as a function of the test pyrometer lamp current. The second part is a scale calibration where the instrument scale is calibrated as a function of pyrometer lamp current. When combined, these two parts result in the calibration of the instrument scale as a function of the brightness or blackbody temperature of the source being observed.

In order to perform the calibration as described, the pyrometer lamp current must be measured to at least 1 part in 1 thousand and preferably to 1 part in 10 thousand. A potentiometer and standard resistor are used for this purpose. An electrical series circuit is set up containing the test pyrometer lamp, resistors or meters normally in the test pyrometer lamp circuit, a continuously variable resistor, a standard resistor, and a lead storage battery. The pyrometer lamp current is controlled with the variable resistor and determined with the potentiometer by measuring the voltage drop across the standard resistor.

Two observers perform the first part or lamp calibration of the test instrument; one observer makes the brightness match while the other determines the lamp current with the potentiometer. One point on the brightness calibration is obtained as follows. The strip-lamp current is determined. Then one observer makes two brightness matches on the strip lamp using the NBS instrument, the first approaching the match with the filament initially darker than the strip and the second with the filament initially brighter. These matches will be designated as dark to bright and bright to dark respectively. After each match, the current in the pyrometer filament is determined. Next the observer shifts himself and the strip lamp to the test instrument and makes 4 matches, dark to bright, bright to dark, bright to dark, and dark to bright. Returning to the NBS instrument, two more matches, bright to dark and then dark to bright, are made; and the strip-lamp current again determined. Bracketing the eight brightness matches with two strip-current determinations serves as a check on any drift of the strip-lamp current and therefore the brightness temperature. The drift is usually negligible. The data for this one calibration point for the pyrometer lamp are completed after the observers switch roles (brightness matching and current measuring) and the process repeated. In summary, the brightness comparison of the test and NBS pyrometer at a given temperature consists of four matches on the NBS instrument and four on the test instrument by each of two individuals.

The data obtained by the two individuals are separately averaged, each of the average NBS pyrometer lamp currents are converted to brightness temperatures through the primary calibration, and finally these temperatures are corrected for any mean effective wavelength differences

[29] By negligible is meant an effective wavelength for which the temperature correction when observing strip lamps is about 1/10 of the other uncertainties in a calibration.

between the NBS and test instruments. Thus a lamp-calibration point consists of two test pyrometer lamp currents and corresponding brightness temperatures of the tungsten strip lamp determined by two observers at the mean effective wavelength of the test instrument.

d. Low-Range Calibration

The brightness calibrations are performed range by range. The low range is calibrated first, because its calibration is used in the calibration of the other ranges. Six calibration points similar to that described in section 5.1.c are obtained for the low range, about 800 to 1250 °C. Other points in the low range are obtained by interpolation. For one class of optical pyrometers, calibrated at NBS for a number of years, a table of current versus temperature representing an average smoothed low-range calibration has been obtained. Temperature differences between this table and the six calibrated points are plotted as a function of current, and a curve best fitting these points is drawn. This is similar to the Δt curve obtained for the low range of the NBS primary calibration. A typical example is shown in figure 16. For instruments for which an average calibration does not exist, eight calibration points are obtained at equal current intervals in the low range and a 4th- or 5th-degree equation is fitted to the eight points by the method of orthogonal polynomials [16, 17].

The low-range calibration is completed by determining the current corresponding to the cardinal readings on the pyrometer scale or meter for which a temperature is to be reported. This, together with the Δt curve and the table or the 4th- or 5th-degree equation, permits a blackbody temperature to be obtained for each of these cardinal points.

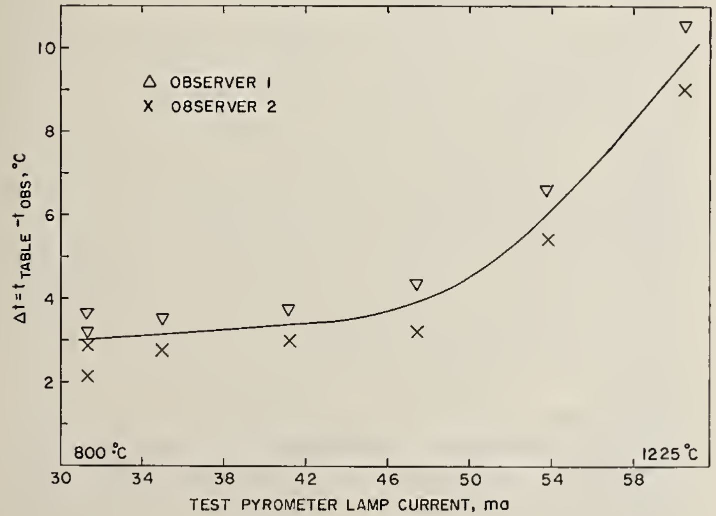


Figure 16. *A typical low-range Δt calibration curve for a commercial optical pyrometer.*

e. High-Range Calibrations

The high ranges of an optical pyrometer are calibrated by determining the A value for each of the absorbing glasses as a function of blackbody temperature. The A value is calculated using eq (1–9) in which T_j is the apparent temperature determined from the low-range calibration using the current corresponding to a brightness match, through the absorbing glass, of a source having a brightness temperature T_i. The temperature T_i is determined by the NBS instrument and must be corrected for the mean effective wavelength of the test pyrometer.

Observations at a particular temperature are taken in a manner similar to that described for the low range. Since A values are usually linear functions of temperature, observations are limited to three temperatures in a range. However, each observer takes two sets of observations at each point to improve the precision of the mean.

A values for each range are plotted as a function of pyrometer lamp current or source temperature. As in the low-range calibration, pyrometer lamp currents corresponding to the cardinal points to be reported are determined. Apparent temperatures are obtained for these currents using the low range Δt curve. The T_{app} together with the corresponding A values are then used in eq (1–9) to obtain a temperature calibration. Mathematically

$$\frac{1}{T}=\frac{1}{T_{\text{app}}}-A=\frac{1}{T_{\text{app}}}-\left(\frac{1}{T'_{\text{app}}}-\frac{1}{T_i}\right) \qquad (5\text{–}1)$$

where the apparent temperature associated with the A value is primed to emphasize that its value depends on how the A value curve is drawn and may be different from T_{app}. Since unexplainable observer differences exist in brightness matches, a compromise is made when drawing the A value curve—a compromise between completely smoothing the data with the theoretically predicted curve and exactly following the experimentally determined A values. Figure 17 is a typical example of an A value curve.

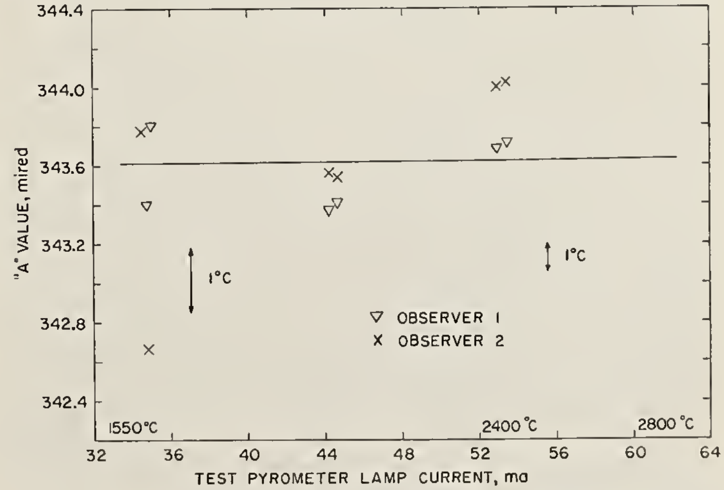


Figure 17. *A typical A value determination for an upper range of a commercial optical pyrometer.*

Optical pyrometers are calibrated up to 2400 °C (as of May 1961) using tungsten strip lamp sources.[28] Usually for instruments used to 2800 or 3200 °C actual observations are not made above 2400 °C. The A value is extrapolated above 2400 °C using the theoretically predicted shape, which is usually a constant. For ranges which extend to about 4200 °C, in addition to using a tungsten strip lamp up to 2400 °C, the positive crater of a carbon arc, at a brightness temperature of about 3530 °C with spectrographically pure graphite electrodes or between about 3630 and 3800 °C with projector pregraphited carbons, is also used to obtain the A value. Since the carbon arc is not as stable as a strip lamp, observations are often made simultaneously with two observers making brightness matches with the NBS pyrometer and the test pyrometer simultaneously.

Changes in the brightness temperature with wavelength in the case of carbon arcs are sufficiently small so that effective wavelength corrections can be neglected. This is because the positive crater of a carbon arc is very close to a gray body with an emittance of about 0.77 in the visible spectral region [14]. Thus the color temperature in this case is the temperature; and for a brightness temperature of 3800 °C, the temperature would be about 4000 °C. Such a range of brightness to color temperature is not sufficient to produce a significant change in brightness temperature for a 0.01 μ wavelength shift, the maximum normally observed.

In some optical pyrometers the range to 4200 °C is reached by using two absorbing glasses in series. These may be calibrated at lower temperatures and the A values added. When this is possible the uncertainty of the calibration is often less.

5.2. Tungsten Strip Lamps

a. Calibration Range

Gas-filled tungsten strip lamps are normally calibrated at NBS at brightness temperatures from 800 to 2300 °C. The lower limit is set by the fact that very few calibrations are ever requested below this temperature and because the eye's contrast limen[15] is already quite high at 800 °C. However, Lovejoy [7], by removing the red glass, has used a conventional laboratory optical pyrometer to brightness temperatures as low as 590 °C with a standard deviation of about 7 °C. The upper brightness temperature limit of 2300 °C has evolved from years of experience of how well the lamps withstand deterioration at high temperatures. Obviously, the limit is somewhat arbitrary. One can operate a lamp above a 2400 °C brightness temperature; but on the other hand, one should not leave a lamp at even a 2300 °C brightness temperature needlessly. Though lamps are usually calibrated at intervals of 100 deg C, a calibration at any temperatures from 800 to 2300 °C will be supplied if requested.

[28] See footnote on p. 19.
[15] See footnote on p. 8.

b. Mounting and Orientation

The first step in the calibration of a tungsten strip lamp of the T24 type at NBS is to determine the orientation for which the lamp is to be calibrated. The lamp is mounted on the optical axis of the NBS pyrometer about 60 cm from the pyrometer lamp with the tungsten strip approximately vertical. With the strip at a brightness temperature of about 1600 °C, the lamp is rotated about the axis of its envelope so that radiation reflected from the lamp envelope onto the tungsten strip and then reflected by the strip does not enter the pyrometer. This condition is determined in the following manner. The reflection of the strip from the glass envelope is observed from the side of the cylindrical envelope away from the pyrometer and the eye moved until the image appears to be in line with the filament. This determines the direction of the rays which are reflected from the envelope and then reflected from the strip. The direction of the secondary reflection from the strip is obtained by looking down from above the strip. If possible, the lamp is oriented so that the pyrometer axis is normal to the strip. If it is found that a reflection into the pyrometer occurs when the pyrometer optical axis is normal to the filament, a suitable position of the lamp close to this normal is selected. Finally the lamp is adjusted so that the tungsten strip at the notch is vertical as determined by a plumb line.

With the optical pyrometer axis horizontal and aimed at the filament notch, a small ink mark is made on the envelope of the lamp at the position where the optic axis strikes the envelope on the side away from the pyrometer. The lamp is taken down and a small arrow etched on the glass such that the head of the arrow just touches the ink spot.

The etching is performed using hydrofluoric acid (48 percent) and a wax protective coating commonly referred to as a resist. Resist formula P–1 described in NBS Circular 565 [18] is used. A large needle is used to inscribe the arrow on the resist and beeswax is placed on and around the resist in the form of a small cup to keep the hydrofluoric acid from coming in contact with any glass not protected with the resist. A 3 min etch appears to be quite satisfactory. After this period of time, the acid is washed off with water, the lamp is cleaned with xylene, then soap and water, and finally dried with a nonabrasive tissue paper.

The lamp is now remounted for final adjustment prior to the actual calibration. With the strip incandescent and some background illumination on the arrow, the latter can be seen in the field of view of the pyrometer; and the lamp is oriented so that the arrowhead appears at the notch. This orientation is checked and maintained throughout the entire calibration.

At the normal distance at which lamps are calibrated, the angle subtended at the strip by the entrance pupil of the pyrometer varies from about 0.02 radian in the range 1100 to 2300 °C to about 0.05 radian at 800 °C. A detailed description of the lamp orientation, direction of sighting, entrance angle, and room temperature is given in each certificate of calibration so that these conditions can be duplicated by the lamp user.

c. The Electrical System

The source of electric current for the lamps is a bank of storage batteries having a 1600 amp-hr capacity and an emf of 120 v. Coarse control of the lamp current is obtained with an NBS-constructed air-ventilated resistor made of coils of chromel A and nichrome wire connected in parallel through knife switches. In parallel with this arrangement are two slide-wire reostats for fine control permitting changes of a few parts in 10,000. The polarity of the electrical connection to the lamp is identified on the certificate. Depending on the lamp, currents from a few amperes to 75 amp are required. These are determined to an accuracy of about 1 part in 10,000 with a potentiometer by measuring the potential difference across a 0.001-ohm calibrated shunt resistor placed in series with the lamp. The current drift during the time required to make a set of 4 brightness matches is usually less than the equivalent of 1 deg C.

d. Calibration

Gas-filled lamps are annealed at a brightness temperature between 2325 and 2350 °C for 2 hr just prior to the calibration. The first temperature calibrated is the highest point requested. Observations are made using a procedure similar to that used in calibrating optical pyrometers. Two observers each make four matches (bright to dark, two dark to bright, bright to dark) at each of the temperatures to be reported. In the usual case of calibrating at 100 deg C intervals, the observers wait 10 min between points (after the initial 2 hr anneal) to allow the lamp to reach equilibrium after each temperature change. However, at 1000 and 900 °C, a 15 min wait is employed and at 800 °C, 20 min. For temperature changes greater than 100 °C even longer waiting periods are used.

The brightness temperatures of tungsten strip lamps calibrated at NBS are reported to correspond to a wavelength of 0.653 μ. The actual wavelength for the observations between 800 and 2300 °C varies from 0.657 to 0.653 μ with abrupt changes in wavelength whenever the range of the pyrometer is changed. However the greatest difference in the actual wavelength and that reported only amounts to an error in brightness temperature of about one-seventh the uncertainty stated.

5.3. Precision and Accuracy[30]

a. Definition of Precision and Accuracy

By the precision of a measurement, one usually means how well the measurement is reproduced. More specifically, if NBS calibrates an optical pyrometer a number of times and if the pyrometer is stable, a measure of the precision of the calibration or calibrations is the standard deviation of the entire population comprising the calibrations. If the entire population is not available, the standard deviation of the population is estimated by the standard deviation of a sample of the population, and it should be kept in mind that such estimates are subject to considerable variation from sample to sample when the size of the sample is small [19].

The concept of accuracy refers to how well a particular value agrees with the correct value. However, except in a situation where a material standard defines a unit of measurement, such as the meter bar previous to 1960, the correct value is not known and the accuracy of a particular result can never be exactly determined. An experimenter can make an estimate of the constant or systematic errors of a measurement, and this information is certainly useful. However, since such estimates are a matter of judgment they vary greatly from one individual to another, and an objective interpretation on the meaning of the errors is even more difficult if not impossible to make.

There is a manner of obtaining an estimate of accuracy, at least for temperature calibrations on the IPTS, which does not possess these limitations. The various national standards laboratories throughout the world independently attempt to experimentally realize the IPTS. Moreover, many of these laboratories are continually trying to improve their realization of the scale, and differences among the laboratories are probably the best indication available of how well the scale is being realized. Therefore, a very useful measure of the accuracy of a temperature calibration relative to the IPTS is the standard deviation of the population consisting of the means of the population of the temperature calibrations performed in each of the national laboratories. In practice numerical results are usually not available from all the national laboratories, and therefore only a sample or estimated standard deviation can be determined. Of course, any constant systematic error that exists in all the national laboratories is not revealed in this manner. But under these circumstances neither would it be accounted for in any other way. Thus it is believed that the above standard or sample standard deviation is the best available estimate of the accuracy of realizing the IPTS.

[30] The authors thank C. Eisenhart, H. H. Ku, and J. Mandel of the National Bureau of Standards for their interest and helpful discussions concerning this section.

b. A Statistical Model for Calibration Errors

There are a number of sources contributing to the lack of precision and accuracy in optical pyrometer and tungsten strip lamp calibrations. These have already been discussed in various parts of the paper and are summarized in the following statistical model.

$$t^l_{ijk}=t_{\text{Int}}+e^l+a_i+b_j+c_k+d \qquad (5\text{–}2)$$

where t^l_{ijk} represents the temperature obtained from a single set of observations [31] by a single individual with a particular apparatus in a particular national laboratory. In eq (5–2) t_{Int} is the correct temperature on the IPTS, e^l is the (random) error of the lth set of observations of an observer,[32] a_i is the systematic error of the ith observer, b_j is the systematic error of the jth apparatus, c_k the systematic error of the kth national standards laboratory and d is the constant systematic error common to all the laboratories. All the errors except d are assumed to be normally and independently distributed [19] with mean or expected value zero and variances $V(e)$, $V(a)$, $V(b)$, and $V(c)$. From theory of statistics, then, the variance of t is equal to the sum of the variances of the errors or

$$V(t)=V(e)+V(a)+V(b)+V(c). \qquad (5\text{–}3)$$

No statistical (or other type) information can be obtained for d until it is discovered in one or more laboratories, and then it becomes part of the c_k's of the remaining laboratories.

Estimates of the variances in eq (5–3) or their square roots, i.e., the standard deviations, can be obtained from the results of experiments by the components of variance technique [20]. For example, if one observer performs many calibrations at one temperature on the same instrument using the same apparatus in the same standards laboratory, all the parameters on the right hand side of eq (5–2) remain constant except e^l. Therefore the variance of these individual temperature determinations is an estimate of $V(e)$. With $V(e)$ determined, a large number of observers can be used to obtain an estimate of $V(a)$. Similarly estimates of $V(b)$ and $V(c)$ can be obtained. This involves a tremendous amount of work and in addition is complicated by the fact that any changes or drifts in the instruments must also be taken into account. Nevertheless, an attempt has been made at NBS to begin to determine the variances in this model. Preliminary estimates for the standard deviations of these errors are listed in table 3 for calibrations of optical pyrometers and tungsten strip lamps at 1063 and 2300 °C. Only an upper limit for the estimate of the standard deviation of c could be determined because of the incompleteness of the data from the 1957–58 international comparison of strip lamps discussed in section 4.

TABLE 3. *Preliminary estimates for the standard deviations in deg C of various errors associated with optical pyrometer and strip lamp calibrations on the IPTS*

e is the random error of a set of observations by a single observer and a, b, and c are systematic errors associated with the observers, the apparatus, and the national standards laboratory, respectively.

	Strip lamps		Pyrometers	
	1063 °C	2300 °C	1063 °C	2300 °C
$s(e)$	0.3	0.9	0.3	1.4
$s(a)$	0.5	0.8	0.5	1.8
$s(b)$	0.3	0.6	0.3	1.4
$s(c)$	<0.5	<2.0	<0.5	<2.0

It is interesting to note that the estimated standard deviations of the errors associated with the calibration of pyrometers at 1063 °C turned out to be the same as that for strip lamps. At first this is surprising because twice as many brightness matches are necessary for a pyrometer calibration than for a strip-lamp calibration. Analyzing the brightness matches more carefully, however, one notes that when observers match high or low with the NBS pyrometer, they also match high or low respectively with the test pyrometer. At 2300 °C the correlation does not appear to exist, probably due to different pyrometer-lamp brightness temperatures in the test (~1050 °C) and NBS instrument (~1300 °C).

c. Uncertainties on Certificates

Ideally, the uncertainties stated on certificates of calibrations should be related to the estimated standard deviation of t. Unfortunately, adequate information has not yet been obtained to make this sufficiently quantitative to be meaningful. Thus, until sufficient data are obtained, preliminary estimates of the type given in table 3 together with the available data on the stability of strip lamps and pyrometers have been used to make "judgement type" estimates of the sum of the errors in eq (5–2), assuming the signs associated with the errors are the same. These are called maximum uncertainties on the calibration certificates. For optical pyrometers they are usually given as ±4 deg C at 800 °C, ±3 deg C at 1063 °C, ±8 deg C at 2800 °C, and about ±40 deg C at 4000 °C. For strip lamps they are ±5 deg C at 800 °C, ±3 deg C at 1000 and 1100 °C, and ±7 deg C at 2300 °C. It is presently (1961) felt that these errors are more conservative at the lower temperatures than at the high temperatures. It should be emphasized that these uncertainties as stated on the certificates do not represent a

[31] For strip-lamp calibrations, a single set of observations means the 4 brightness matches (dark to bright, 2 bright to dark, dark to bright) and the associated electrical current measurements. For optical pyrometer calibrations, a single set of observations means the 8 brightness matches of the NBS and test pyrometers and associated electrical current measurements described in section 5.3.

[32] For simplicity it has been assumed that the random error population for each observer is the same. This is only approximately true in practice.

standard deviation or some multiple of a standard deviation. It is hoped, however, that something more statistically meaningful can be incorporated in the certificates in the near future.

d. Differences Between the IPTS and TTS

When it is necessary for someone to obtain a temperature on the Thermodynamic Temperature Scale (TTS) [21] with an instrument calibrated at NBS on the IPTS, the estimated difference between the two scales is required. Above 1063 °C this is relatively easy to obtain because the IPTS would also be the TTS if the second radiation constant C_2 and the freezing point of gold t_{Au} were correct. Thus, estimates of the correct values for C_2 and t_{Au} are sufficient to calculate estimated differences between the two scales.

DuMond and Cohen [22] have reported a value of 1.43884 ±0.00008 cm deg for C_2, obtained from their adjusted values of the atomic constants. The freezing point of gold on the Thermodynamic Scale has been redetermined in a number of laboratories during the past 6 years and three independent groups have confirmed the value 1064.5 °C (therm.) [23]. Using these values for C_2 and t_{Au}, estimated differences between the TTS and IPTS have been calculated and are presented in figure 18. Also included in figure 18 is the error incurred in using the Wien equation at 0.65 μ as an approximation for the Planck equation in the IPTS.

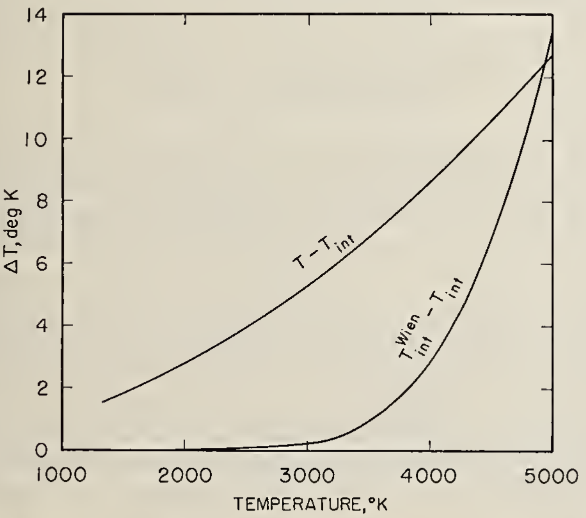


FIGURE 18. *Estimated difference between the Thermodynamic Temperature Scale and the International Practical Temperature Scale, and the error incurred when using the Wien equation (at 0.65 μ) as an approximation for the Planck equation in the IPTS.*

6. Applications

6.1. Temperature Measurements

An optical pyrometer determines the brightness temperature of an incandescent body at the mean effective wavelength between the brightness temperature and the color temperature of the body. If the spectral emittance of the particular part of the body sighted on is known, the temperature of the body may be determined from the following equation

$$\epsilon_{\lambda_{T_B-T_C}}(T)N_{b\lambda_{T_B-T_C}}(T)=N_{b\lambda_{T_B-T_C}}(T_B) \qquad (6\text{–}1)$$

or

$$\epsilon_{\lambda_{T_B-T_C}}(T)\left[e^{\frac{C_2}{\lambda_{T_B-T_C}T}}-1\right]^{-1}=\left[e^{\frac{C_2}{\lambda_{T_B-T_C}T_B}}-1\right]^{-1} \qquad (6\text{–}2)$$

where $\epsilon_{\lambda_{T_B-T_C}}(T)$ is the spectral emittance at the mean effective wavelength $\lambda_{T_B-T_C}$, T_B is the brightness temperature of the body at this wavelength, T_C the color temperature, and T the temperature. When Wien's equation is an adequate approximation, eq (6–2) can be reduced to the simpler form

$$\frac{1}{T}=\frac{1}{T_B}+\frac{C_2}{\lambda_{T_B-T_C}}\ln \epsilon_{\lambda_{T_B-T_C}}(T). \qquad (6\text{–}3)$$

Spectral emittances are accurately known for only a few substances and surface conditions. Probably the most accurately known spectral emittances are those for tungsten [6, 24, 25]. An illuminating review of the principles, methods of measurement and the results of investigations on spectral emittances prior to 1939 has been given by Worthing [26]. More recent contributions can be found in the proceedings [27] of the Fourth Symposium on Temperature, Columbus, Ohio (1961).

In the vicinity of the gold point and a wavelength of 6500 A an error of 1 percent in spectral emittance results in an error of only 0.065 percent in temperature. More generally, using Wien's approximation, assuming that the small variation of spectral emittance with temperature may be neglected, and differentiating the equation

$$N_\lambda(T)=\epsilon_\lambda(T)C_1\lambda^{-5}e^{-C_2/\lambda T}, \qquad (6\text{–}4)$$

one obtains

$$\frac{dT}{T}=\frac{\lambda T}{C_2}\frac{dN}{N}. \qquad (6\text{–}5)$$

For the most accurate temperature determination with an optical pyrometer, it is recommended that a blackbody be built into the experimental setup. Then, of course, the spectral emittance is unity and the temperature is equal to the brightness temperature. Often blackbody conditions can be approximated sufficiently well by simply drilling a small hole into a solid or by inserting a small cavity in a molten substance.

6.2. Spectral Radiance Calibrations Using Strip Lamps

Tungsten strip lamps are often used to calibrate the response of spectrographs and spectrometers from about 2500 to 25,000 A. For this purpose, the brightness temperature or spectral radiance of the lamp as a function of wavelength is required. Such a calibration is performed in the Radiometry Section at NBS and is available to the public. At present (1961) the maximum uncertainties reported vary from 3 percent at 25000 A to 8 percent at 2500 A.

Another way of obtaining the spectral calibration of a strip lamp is to calculate it using the brightness temperature from an optical pyrometer determination and published values for the spectral emittance of tungsten. The spectral radiance of a tungsten lamp is given by

$$N_\lambda(T)=C_1\lambda^{-5}[e^{C_2/\lambda T_B}-1]^{-1}$$

$$=\epsilon_\lambda(T)\,\tau_\lambda C_1\lambda^{-5}[e^{C_2/\lambda T}-1]^{-1} \quad (6\text{–}6)$$

where T_B is the brightness temperature of the lamp at wavelength λ, $\epsilon_\lambda(T)$ is the spectral emittance of the tungsten, τ_λ the spectral transmittance of the lamp window or envelope, and T the strip temperature. The procedure for determining $N_\lambda(T)$ at any wavelength is to first solve for T in eq (6–6) using the calibrated value of T_B and the measured or assumed value for τ_λ and published value of ϵ_λ, all at the mean effective wavelength associated with T_B. Then $N_\lambda(T)$ can be calculated for any wavelength for which ϵ_λ and τ_λ are available. For the visible spectral region and infrared to about 25000 A, it is usually adequate to assume τ_λ is constant. If a quartz envelope is used rather than glass, the constancy can be extended down to about 2800 A or less, depending on the type of quartz. Several papers have reported experimental determinations of ϵ_λ for tungsten during the past 10 years [6, 24, 25]. One of the major limitations of this technique is the question of whether the emittance of the tungsten in the lamp being used is the same as that reported in the literature. In addition, the effect of internal reflections and knowledge of the transmittance of the window will be somewhat uncertain. On the other hand, all of these parameters are used in a relative manner, i.e., the spectral radiance is known at about 0.65 μ, and one merely has to compute values at other wavelengths relative to it. As a result, the calculated spectral radiances at wavelengths other than 0.65 μ are usually only a few percent more uncertain than the spectral radiance at 0.65 μ which is obtained directly from the brightness temperature.

In using the tungsten lamp for spectral calibrations one should take the same precautions of orientation and alinement described in sections 3 and 5. In particular, one should try to use the strip lamp at the same entrance angle at which it was calibrated, especially when this angle is small and the lamp envelope appears to be inhomogeneous in the region where the beam exits.

6.3. Secondary Standards

A laboratory or industrial group that requires high accuracy in its optical pyrometry work or that requires only moderate accuracy but uses many strip lamps or optical pyrometers should consider maintaining its own secondary standards. It is often asked which is preferable, a strip lamp or optical pyrometer as a secondary standard to maintain the IPTS above 1063 °C. There is no unique answer to this question. It will depend on some factors that only the user himself is aware of, factors such as the manner and frequency with which the secondary standards are used and the money and personnel available for this work. Some of the factors that should be considered are listed in table 4.

6.4. Recommendations for Achieving High Accuracy and Precision

When high accuracy is the primary consideration in maintaining or making measurements on the IPTS, a few procedures should be emphasized. Both optical pyrometers and tungsten strip lamps change with use. Therefore, in order to obtain high accuracy, a laboratory should use one calibrated strip lamp or optical pyrometer infrequently and compare the strip lamps or pyrometers used regularly to it. As emphasized previously, great care should be taken concerning the orientation and alinement of the strip lamps, and vacuum lamps should be used whenever possible.

TABLE 4. *Relative merits of strip lamps and optical pyrometers as secondary standards for the IPTS*

	Strip lamps	Optical pyrometers	Section discussed
Stability		Somewhat better	2.1, 3.4
NBS calibration uncertainty	At present (1961) about the same		5.12
Brightness temperature range	800–2300 °C	800–4000 °C, and higher	5.6
Care necessary for orientation and ambient temperature control.	Considerable	Very little	3.4
Time to reach equilibrium	Minutes to an hour	Seconds to a minute	2.1, 5.9
Cost of instrument	Considerably less		
Cost of NBS calibration	Less		
Cost of additional apparatus for most accurate use.		Somewhat less.	

For optimum precision and accuracy in the use of pyrometers, laboratories should request NBS to calibrate their pyrometer as a function of pyrometer filament current. The laboratory should then use a standard resistor and a sufficiently accurate potentiometer to determine this current. A multiturn smooth turning rheostat is highly desirable for varying the filament current while making the brightness matches. The precision of matches can often be improved greatly by having the pyrometer mounted rigidly in a comfortable position for a sitting observer. A black cloth thrown over the observer's head and part of the optical pyrometer to shield the observer from any distracting or annoying light is helpful. Observations should always be made from both a dark and a bright filament to a match or disappearance and the two results averaged. If one or two individuals primarily use the pyrometer, make sure that their technique of matching does not give results very different from the average of 5 or 6 observers. In addition, if non-blackbodies are often used, it is well to use 5 or 6 observers to determine if any observer has a very unusual relative luminosity curve. The standard deviation of the mean effective wavelength due to luminosity factor differences has been reported [28] to be about 8 A, which in reading a strip lamp at 2300 °C with a pyrometer having constant A value absorbing glass, amounts to about 0.4 degree.[33] Of greater relative importance than the relative luminosity factors for affecting the effective wavelengths are differences in spectral transmittance of the red glasses in pyrometers. Methods for determining the effective wavelengths of optical pyrometers were described in section 5. For convenience, table 5 summarizes the various recommendations for the practice of precise and accurate optical pyrometry.

[33] However, in a primary calibration an error of 8 A in the mean effective wavelength between 1063 and 2300 °C is equivalent to an error of about 3½ °C at 2300 °C.

TABLE 5. *Recommendations for the precise and accurate use of optical pyrometers and tungsten strip lamps*

Recommendation	Section discussed
Use the instrument infrequently	2.1, 6.4
Take the necessary precautions in orienting and alining strip lamps	3.4, 5.3, 5.7
Use a source whose image is large compared to that of the pyrometer filament	3.3
Use several observers	5.11, 6.4
The observer should be in a comfortable position, have a hood, and have the pyrometer rigidly mounted	6.4
Determine the effective wavelength of the pyrometer when observing non-black sources	1.6, 1.7, 5.2, 6.4
Use the pyrometer lamp current as the parameter to relate the brightness match	5.3, 6.4
Use a vacuum strip lamp for brightness temperatures below 1400 °C	3.3

6.5. Fundamental Limitations

The fundamental limitation in visual optical pyrometry is the sensitivity of the human eye. Lovejoy [7], using the results of an investigation of contrast thresholds or limens (see footnote 15) reported by Blackwell [29], calculated the expected observer standard deviation temperatures for the mean of a set of matches consisting of a bright filament to disappearance and a dark filament to disappearance for a pyrometer having a 0.05 radian exit angle, a 0.7 mm exit pupil, and a 0.038 mm actual and 10 min apparent angular filament width. The standard deviations ranged from 0.2 deg C at 1400 °C to 0.3 deg C at 1063 °C and increased to 1.6 deg C at 800 °C,[34] and agreed well with his experimental values.

Another basic limitation in visual pyrometry is the uncertainty of the observer's relative luminosity function. This function is required in a primary calibration of optical pyrometers at temperatures above the gold point, and its uncertainty corresponds to an equivalent uncertainty of about 1 to 1½ deg C in the primary calibration at 2400 °C. The effect of the uncertainty in the relative luminosity factors could be reduced by using a narrower spectral bandwidth in optical pyrometers. However, then one would begin to be even more limited by the eye's contrast sensitivity. Most optical pyrometers appear to be designed so that the two limitations are about equal at 2400 °C.

6.6. Photoelectric Optical Pyrometers

During the past 5 years, optical pyrometers which employ a photomultiplier tube rather than the eye as a detector have come into existence. Such instruments have been developed in the national standards laboratories of the U.S.S.R. [30], Australia [31], and the United States [1]. They have considerably greater sensitivity and precision (~0.01 deg) than the visual instruments and can use a much smaller spectral bandwidth. It is expected that photoelectric pyrometers will make possible at least an order of magnitude greater accuracy in optical pyrometry. However, in order to achieve this a number of difficult problems will have to be solved. Two of these are obtaining a "blackbody" with an emittance approaching 0.9999 and determining the ratio of two beams of radiant energy with an accuracy of 0.01 percent. These and other challenging problems, and the promising increase in the accuracy of high-temperature measurement if they are solved, have stimulated a new and exciting activity in the field of optical pyrometry.

[34] Corresponding standard deviations for higher temperatures can be obtained from the relation between two temperature differentials obtained from Wien's equation. This relation is $dT=(T/T_A)^2dT_A$ where T represents the higher range temperature and T_A its corresponding apparent temperature as seen through the absorbing glass. At 2400 °C the resulting standard deviation is about 1 deg C.

7. References

[1] R. D. Lee, The NBS photoelectric pyrometer of 1961, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[2] H. F. Stimson, The International Practical Temperature Scale of 1948, J. Research NBS **65A,** 139 (1961); The International Temperature Scale of 1948, J. Research NBS **42,** 209 (1949).

[3] C. O. Fairchild and W. H. Hoover, Disappearqnce of the filament and diffraction effects in improved forms of an optical pyrometer, J. Opt. Soc. Am. **7,** 543 (1923).

[4] W. E. Forsythe, Optical pyrometry, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1941) p. 1115.

[5] C. R. Barber, Factors affecting the reproducibility of brightness of tungsten strip lamps for pyrometer standardization, J. Sci. Instr. **23,** 238 (1946).

[6] J. C. DeVos, A new determination of the emissivity of tungsten ribbon, Physica **20,** 690 (1954).

[7] D. R. Lovejoy, Photometry of the optical pyrometer and its use below 800°C, J. Opt. Soc. Am. **49,** 249 (1959).

[8] F. A. Cunnold, The optical system of the disappearing filament pyrometer, Proc. Roy. Soc. (London) **152A,** 64 (1935).

[9] J. C. DeVos, Evaluation of the quality of a blackbody, Physica **20,** 669 (1954).

[10] J. Vollmer, Study of the effective thermal emittance of cylindrical cavities, J. Opt. Soc. Am. **47,** 926 (1957).

[11] A. Gouffé, Corrections d'ouverture des corps-noirs artificiels compte tenu des diffusions multiples internes, Revue d'optique **24,** 1 (1945).

[12] H. G. MacPherson, The carbon arc as a radiation standard, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York (1941) p. 1141.

[13] M. R. Null and W. W. Lozier, The carbon arc as a radiation standard, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[14] J. Euler, The graphite carbon arc as a standard source of intense radiation, Sitzber. Heidelberg Akad. Wiss. **4,** 418 (1956–57).

[15] A. Bauer and P. Schultz, Eingeengte Xenon-Hochdruckentladungen höher Stromdichte, Z. Physik **155,** 614 (1959).

[16] R. A. Fisher, Statistical Methods for Research Workers (Hafner Publishing Co., New York, 1954) 12th ed., p 147.

[17] R. L. Anderson and E. E. Houseman, Tables of orthogonal polynomial values extended to $N=104$, Iowa Agr. Exp. Sta. Research Bul. 297 (1942).

[18] R. Davis and C. I. Pope, Techniques for ruling and etching precise scales in glass and their reproduction by photoetching with a new light-sensitive resist, NBS Circ. 565 (1955) p. 10.

[19] For definitions and further discussions see J. M. Cameron, Statistics, Fundamental Formulas of Physics, edited by D. H. Menzel (Dover Publications, Inc., New York, 1960) p. 107.

[20] F. A. Graybill, An Introduction to Linear Statistical Models (McGraw-Hill Book Company, Inc., New York, 1961), vol. I, ch. 6.

[21] H. F. Stimson, Heat units and temperature scales for calorimetry, Am. J. Phys. **23,** 615 (1955).

[22] J. W. DuMond and E. R. Cohen, Least squares adjustment of the atomic constants, 1952, Revs. Modern Phys. **25,** 691 (1953).

[23] H. Moser, Review of recent determinations of thermodynamic temperatures of fixed points above 419°C, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[24] R. D. Larrabee, The spectral emissivity and optical properties of tungsten, J. Opt. Soc. Am. **49,** 619 (1959).

[25] C. Tingwaldt, New optical methods for the determination of thermodynamic temperatures of glowing metals, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[26] A. G. Worthing, Temperature radiation emissivities and emittances, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1941) p. 1164.

[27] Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[28] D. R. Lovejoy, Accuracy of optical pyrometry in the range 800°C to 4000°C, Can. J. Phys. **36,** 1397 (1958).

[29] H. R. Blackwell, Contrast thresholds of the human eye, J. Opt. Soc. Am. **36,** 624 (1946).

[30] V. V. Kandyba and V. A. Kovalevskii, A photoelectric spectropyrometer of high precision, Doklady Akad. Nauk S.S.S.R. **108,** 633 (1956).

[31] J. Middlehurst and T. P. Jones, A precision photoelectric optical pyrometer, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

U.S. GOVERNMENT PRINTING OFFICE: 1962

U.S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics. Electrolysis and Metal Deposition.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Crystal Growth. Physical Properties. Constitution and Microstructure.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Applications Engineering.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Solid State Physics. Electron Physics. Atomic Physics.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Molecular Kinetics. Mass Spectrometry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Interval Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.