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# A Laboratory Optical Pyrometer: Notes on Its Design and Operation

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# A LABORATORY OPTICAL PYROMETER: NOTES ON ITS DESIGN AND OPERATION

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The writer was confronted with the problem of measuring the temperature of a tungsten wire enclosed in an evacuated tube. A thermocouple could not be used because it would be certain to apply unknown torques to the wire and also to disturb the temperature distribution along the wire. An optical or radiation method of temperature measurement would overcome both of these difficulties. An optical pyrometer suitable for accurate temperature determinations and flexible enough to be of general use in a physical laboratory is not on the market at the present time. This led the writer to the task of designing and constructing the instrument described in this article. For the benefit of those who are not familiar with optical pyrometry a brief sketch of the theory and design of a Holborn-Kurlbaum optical pyrometer has been included.

## GENERAL THEORY

In figure 6 is shown a schematic diagram of a Morse or Holborn-Kurlbaum type optical pyrometer.[1] *A* is the background filament whose temperature is to be determined, *B* is a lens which forms a real image of *A* at *D, C* and *E* are limiting diaphragms, *D*

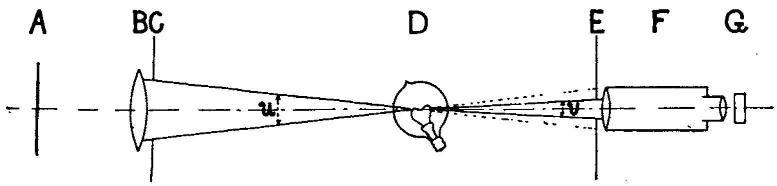


Fig. 6. Schematic diagram of Holborn-Kurlbaum type optical pyrometer.

is the pyrometer-lamp, *F* is a telescope focused on *D* and the image of *A, G* is a monochromatic screen. In making a temperature determination the current thru *D* is adjusted so that the filament of *D* disappears against the image of *A*. Then the temperature is read from the current-temperature calibration curve of the pyrometer.

The calibration of the pyrometer is effected by replacing *A* by a "black-body furnace" [2] maintained at a temperature which can be measured with a gas-thermometer. (The gas-scale has been extended by Day and Sossman to the melting points of gold and palladium which they found to be 1335.6°K and 1822.5°K respectively.) With the aid of Wien's Equation,

$$E_L = C_1 L^{-5} e^{-C_2/LT},$$

where $E_L$ is the energy of wave-length $L$ radiated by a black-body at a temperature of $T$°K, $C_1$ and $C_2$ are constants, and $e$ is the base of Neperian logarithms, the calibration can be extended to higher temperatures.

Suppose some sort of an absorbing screen, which transmits a fraction $t$ of the radiated energy, is placed between $A$ and $D$, and that the body is at an unknown temperature $S$°K. Wien's equation for this body is

$$tE_0 = tC_1 L^{-5} e^{-C_2/L S_0}.$$

Also suppose that a black-body at a temperature of $S$°K (within the range of the gas-thermometer) appears equally bright through the pyrometer when it is not viewed through the absorbing screen. Wien's equation is

$$E = C_1 L^{-5} e^{-C_2/LS}.$$

Now since $E = tE_0$ we have

$$\text{Log}_e\ 1/t = C_2\ (1/S - 1/S_0)/L$$

in which $S_0$ is the only unknown; the present accepted value of $C_2$ is 14320 micron degrees.[15] Thus with this relation available the black-body furnace may be maintained at a constant temperature — the melting point of gold, for example — and any number of points for the current-temperature curve may be obtained by using absorbing screens of various transmissions; of course these points will all correspond to temperatures below 1336.5°K. After this part of the curve has been plotted, it can be extended in the manner described in the first part of this paragraph.

In general a hot body does not emit as much energy as a black body at the same temperature [2], [10], nor is this fractional emission the same for all bodies. For example, a stick of carbon emits much more energy than a piece of polished platinum at the same temperature. In this case, if a deep hole of small diameter be present in the carbon stick and a similar one in the piece of platinum, the holes will appear equally bright and will be as bright as a black-body at the same temperature. Suppose the platinum at a temperture $T$°K is emitting a fraction $r$ of the energy that a black-body would emit if it were in the same thermal state, and let $S$ be the temperature of a black-body which appears as bright through the pyrometer as the radiating platinum. Then if $E$ be the energy of wavelength $L$ emitted by each,

$$E = C_1 L^{-5} e^{-C_2/LT} . r$$

and

$$E = C_1 L^{-5} e^{-C_2/LS}$$

Equating the right-hand members, we have

$$re^{-C_2/LT} = e^{-C_2/LS}$$

or

$$1/T = 1/S + \log r . L/C_2.$$

Since the hole in the platinum is emitting like a black-body, its temperature determination will yield the true temperature of the platinum. The temperature $S$ may be found in the usual manner and, by means of the above equation, $r$ may be calculated. The number $r$ is called the "emissivity" of the substance.[3,14]. It varies from substance to substance and with the condition of the surface for the same substance, as well as with the temperature and with the wavelength of the light used in its determination. When $r$ is known and $S$ has been observed, $T$ can be calculated. Thus we have a method for determining the true temperature of a non-black-body.

## THE OPTICAL PYROMETER IN PRACTICE

The objective lens, $B$ of figure 6, should be an achromatic lens of good quality. A rapid rectilinear photographic lens having a focal length of about 25 cm, and a maximum aperture of about F.8 mounted in a barrel with an iris-diaphragm, will serve very well. It should be placed at such a distance from the pyrometer-lamp $D$ that the image of the background $A$ formed at $D$ is much larger than the filament of $D$.

The telescope $F$ is the eyepiece of the pyrometer. It should be of good quality and capable of being focused on objects as near as one meter. The magnifying power should be sufficiently large so that no difficulty is experienced by the observer in fixing on the intersection of the pyrometer-filament and the background image. The resolving power of almost any laboratory telescope is so great that the objective lens (of the telescope ) will need to be stopped down with a limiting diaphragm $E$. When the resolving power is too great, dark bands are seen on either side of the pyrometer filament; these are caused by the diffraction of the light by the filament. Such diffraction-bands make it almost impossible to get an accurate brightness-match. A telescope having an objective lens of 25 cm. focal length and an eyepiece of 18 mm. focal length will be found satisfactory.

The limiting diaphragms *C* and *E* must be of such a size that disappearances of the pyrometer-lamp filament against the background-image are possible. Angle *v* must be smaller than angle *u*. Both *C* and *E* should be as large as possible but their size must be consistent with ability to obtain disappearances—in order to minimize the diffraction effects at the edges of the apertures, and they should be as far from the lamp *D* as possible. A stop *E*, which may be just small enough to be satisfactorily used at the lower temperatures, may prove to be too large when making brightness-matches at the higher temperatures. The larger *E* is, the farther down the temperature-scale can be extended. Therefore it will be well to use at least two different stops when making the complete calibration of a pyrometer.

A pyrometer lamp having a tungsten filament in a spherical bulb 5 cm. in diameter will be found very satisfactory. The filament of such a lamp is usually in the form of a hairpin loop with a small kink at the top of the loop. This kink is useful in that it enables the operator to be certain that he is using the same part of the filament at all times. A lamp having a filament of 0.033 mm. in diameter is useful if the temperature of small objects, such as wires, is to be measured; for larger objects a larger filament will be found more satisfactory. The diameter of the lamp filament should aways be considerably smaller than that of the background-image. When measuring the temperatures of wires it should be remembered that Lambert's Cosine Law of Emission does not hold in general.[16] For example, a tungsten wire appears brighter at the edge than near the center, while the reverse is true for a carbon lamp filament. Consequently, for most accurate work, the pyrometer-lamp filament should be placed parallel to the background-image. If the background-image is large and the brightness-match is made at a point near its center, the filament may be placed so as to cross the image. For most purposes sufficient accuracy will be obtained even though the filament and image are crossed and the image is not large.

The objective lens of the pyrometer, the kink of the lamp filament, and the telescope must be very approximately axially aligned. Therefore provision should be made for a vertical adjustment and for a rotational adjustment about a vertical axis for the lens, for the telescope, and for the lamp. It must also be possible to rotate the telescope through a small angle in a vertical plane through the optical axis of the system; the lamp should be capable of being adjusted in a horizontal direction perpendicular to the optical axis of the system.

After the pyrometer has once been calibrated the relative positions of the parts must remain fixed, otherwise the temperature determinations will be incorrect. It is, however, allowable to move the different parts relatively to one another if the angles $u$ and $v$ are kept the same. Usually it will be found more convenient to recalibrate the instrument than to make adjustments which will keep $u$ and $v$ constant. The focusing of the pyrometer on the background should be accomplished by changing the distance between $A$ and $B$.

Absolutely-monochromatic screens for use at $G$ cannot be obtained, and filters which are very nearly monochromatic transmit so little light that they can be used only in measuring the high temperatures. "Partially-monochromatic" glasses, which absorb so little of the incident energy that they are usable even at relatively low temperatures, are available. Such a filter can be employed if the correct one of all the transmitted wavelengths is selected. This wavelength is called the "effective-wavelength [3,4] of the filter. It is such that, for any definite temperature interval for a particular source, the ratio of the radiation intensities for this wavelength is equal to the ratio of the integral luminosities through the screen used. The effective wavelength of a filter varies with the temperature to be measured, but for most work, if the average value is used, the error will not be too large. For example, an error of 0.001 micron at 2400°K would cause an error of about 1.2° and at 3000°K an error of about 3° if the filter transmitted red light. Filters transmitting red light are most convenient for general use since red light of a sufficient intensity is emitted by a hot body at a lower temperature than that at which light of the shorter wavelengths is radiated. The least relative change of brightness which can just be detected is about the same for red as for blue light but the change in intensity for a given small temperature change of the radiator is greater for blue than for red. Also, diffraction effects are less troublesome when one is using light of the shorter wavelength. Therefore greater accuracy is obtainable when light of shorter wavelengths is used, but the lowest measurable temperature is higher.

Perhaps the most convenient form of absorbing screen to be used between $A$ and $D$ is a rotating "sectored-disk."[4] Disks which allow as little as 1/180 of the incident light to pass through (2° opening) can be very satisfactorily employed. The disk should be placed as near the pyrometer lamp as possible.[5] If it is located near the lens the definition will be bad because of diffraction, and it will be especially bad if the opening of the disk is small and parallel to the background image (as the opening passes through the optical axis of the pyrometer) if the background is a wire. Therefore it is also advisable to have the opening perpendicular to the background when the opening is passing through the optical axis. The transmission of a sectored disc is the same whether the opening is all in one sector or is made up of several smaller sectors the sum of which is equal to the single sector. The transmission is also independent of the speed of rotation of the disc but the rotation must be sufficiently fast to prevent a flicker. Flicker is not only disagreeable for the observer but it also makes the obtaining of brightness-matches an impossibility.

Black-body furnaces are not easily set up, so it is often much more convenient and satisfactory to obtain a calibrated "Standard-Lamp" for which a curve connecting current through lamp filament and brightness-temperature of filament is furnished. This lamp is to be used in place of the furnace. It is usually a lamp having a large filament which requires a large current at a low voltage. In practice the current must be very accurately determined; this is easily done with a standard resistance and a potentiometer. If the effective-wavelength at which the standard-lamp is calibrated happens to be different from the effective-wavelength of the filter $G$ of the pyrometer which it is desired to calibrate, a correction must be made; that is, the brightness-temperatures at the given effective-wavelength must be changed over into brightness-temperatures at the effective-wavelength of the pyrometer filter. This can be done by means of the formula [6,7]

$$1/S_2 = L_2 \ (1/S_1 - 1/T_c)/L_1 + 1/T_c$$

where $S_1$ and $S_2$ are the brightness-temperatures at the effective-wavelengths $L_1$ and $L_2$ respectively, and $T_c$ is the color-temperature. If the standard-lamp has a tungsten filament this change can be easily made since the color-temperatures with the corresponding true-temperatures have already been worked out.[8, 9]

Sometimes, perhaps generally, in laboratory work, a glass window, the wall of a glass tube, or a layer of some transparent medium is present between the source whose temperature is desired and the pyrometer. Since such media absorb some of the incident light it is necessary to correct for their absorptions before the true brightness-temperature of the source can be stated. If the absorbing medium is on such an apparatus that it is possible to put a small incandescent lamp behind the medium, then the temperatures of the lamp for fixed currents can be determined through the absorbing medium and without the medium present. From such data the temperature-corrections may be found for the desired range. If the apparatus is in the form of a closed glass tube it can be placed in the usual position for the sectored-disc, its transmission determined, and the corrections calculated.[11], [12], [13]

Currents through the pyrometer-lamp filament must be accurately known. A potentiometer gives the highest accuracy but, if a number of settings are to be made, the time required is rather long. Therefore a deflection potentiometer is used for the highest grade work. For ordinary purposes a high grade ammeter equipped with an external adjustable (by steps) shunt will be found very satisfactory. The steps should be so chosen that it will always be possible to keep the deflection of the pointer between 100 and 120 on a 150-division scale. The variable resistance to be used in the pyrometer-lamp circuit should be capable of rather fine adjustment. This is readily accomplished by connecting two rheostats of the sliding-contact type in parallel; one should have a resistance of about three times that of the other. The rough adjustment is made on the rheostat of low resistance and the final adjustment on the one of high resistance. Best results will be secured if the adjustment is always made in the same manner, as for example, the brightness-match might be made by gradually increasing the current until the filament disappears against the background-image. If all the settings are made in this manner consistent results can be obtained with a minimum of experience.

## A LABORATORY OPTICAL PYROMETER

Figure 7 shows an optical pyrometer which meets all the conditions listed in the preceding section of this article. It also has a number of adjustments which help make it flexible enough to be of general use in a physical laboratory.

The objective lens *A* is a Bausch & Lomb rapid rectilinear lens having a diameter of 28 mm., and a focal length of 21 cm. Between the two lens-combinations is an iris diaphragm which, when set at the largest aperture, allows the lens to have a speed of U. S.4.

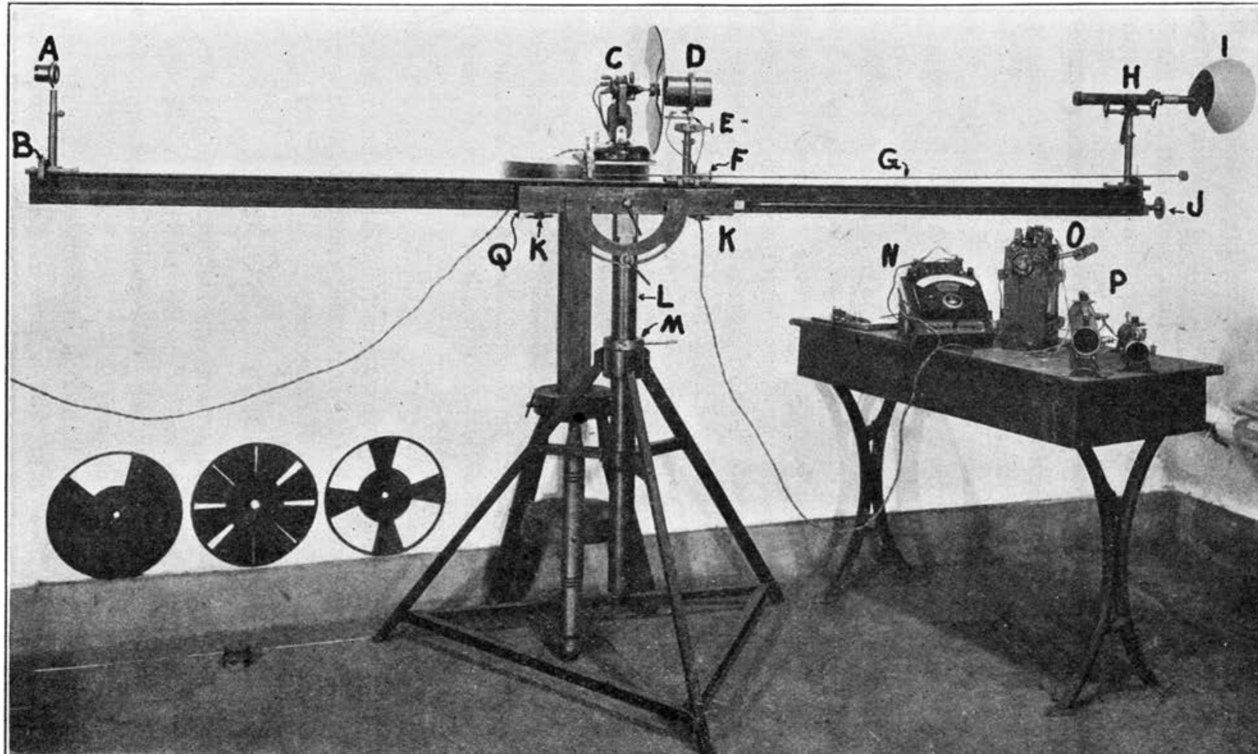


Fig. 7. A Holborn-Kurlbaum optical pyrometer designed so as to be of general use in a physical laboratory.

The telescope *H* was obtained from Wm. Gaertner. The objective lens of this telescope is 30 mm. in diameter and it has a focal length of about 25 cm. It is furnished with two eyepieces, one of 18 mm. and one of 25 mm. focal length. The shorter focal length eyepiece is to be used with fine pyrometer-lamp filaments. In the lens-cap is a 15 mm. hole, the edges of which are beveled on the inside. This serves as the diaphragm *E* of figure 6 for the lower temperatures. At medium and high temperatures this stop is too large, hence three brass discs, which fit snugly in the cap are provided. These have apertures of 13 mm., 10 mm., and 8 mm., respectively. The disk having the 13 mm. hole proved to be the most useful one for the setting shown in figure 7.

Two pieces of red glass, each 1 cm. in diameter and 5 mm. thick, mounted in brass housing, form the monochromatic screen, *G* Fig. 6. The effective-wavelength of this screen, between 1200 and 2400°K, is 0.658 micron. The colored glasses together with effective-wavelength calibration data were obtained from the Nela Research Laboratory of the General Electric Company, Nela Park, Cleveland. The brass housing is equipped with three spring-brass fingers which hold it in place on the eyepiece of the telescope. The black cardboard shade *I* keeps light, other than that coming through the telescope, from entering the operator's eyes. It enables the observer to keep both eyes open, thus making the observation less tiresome.

Telescoping-tube standards allow the objective lens and the telescope to be adjusted vertically and to be rotated about vertical axes. The telescope rests in the two V-shaped pieces of an ordinary laboratory telescope-clamp. In each arm of the rear 'V' is a thumbscrew. These thumbscrews make possible the small adjustments which are usually necessary to bring the axis of the telescope in coincidence with the optical axis of the pyrometer.

The pyrometer-lamp is mounted on the standard shown at D in figure 7. It is inside of the black cylindrical tube which prevents reflection of light from the outside of the lamp-bulb. Figure 8 shows the standard more in detail. The white porcelain lamp-socket is screwed to a round brass disc which is held in a recess in the square base-plate by two spring clips; this permits the lamp to be turned about its axis until the filament is perpendicular to the optical axis of the pyrometer. The square base-plate is fastened to a ring *R* which slides on another ring *S* to which it is held by two spring clips. The ring *S* stands on a plate which can be moved horizontally by turning the knurled head *E*. The rings make it

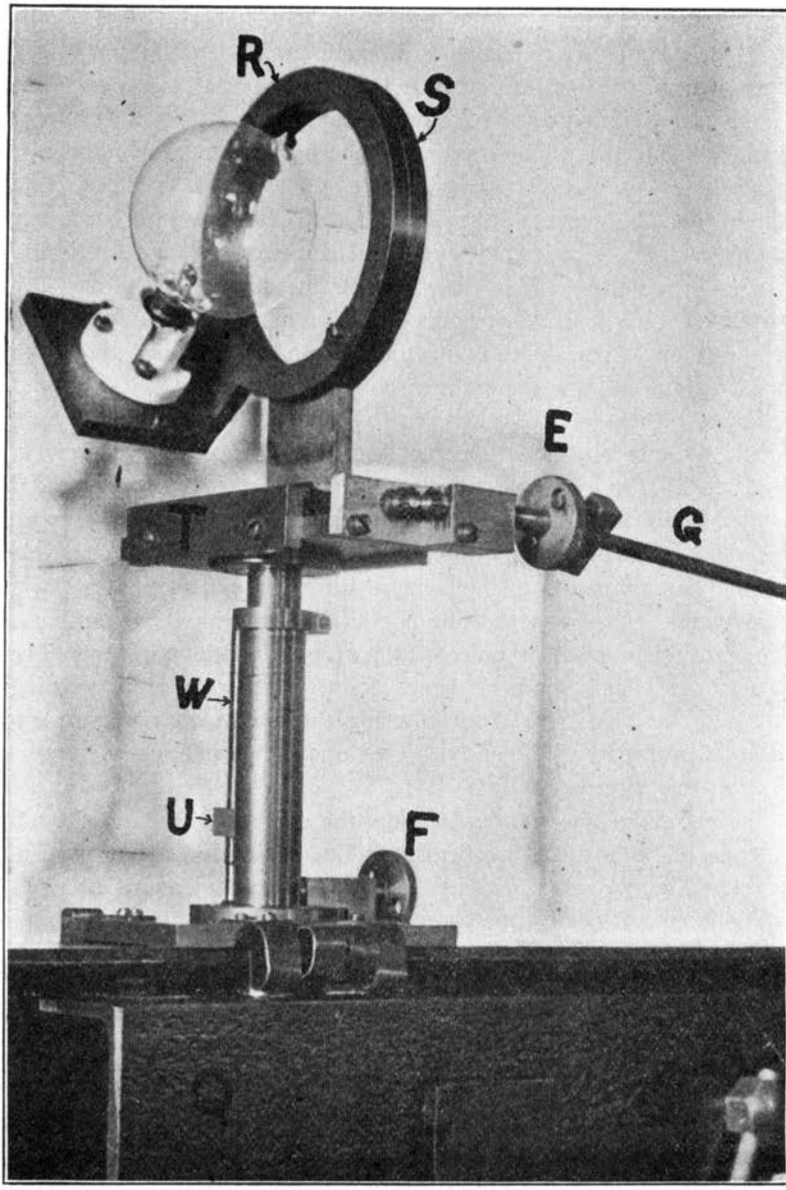


Fig. 8 Mounting for the optical pyrometer lamp which permits of horizontal and vertical adjustment by the observer while he is looking at the filament through the telescope.

possible to rotate the lamp about the optical axis of the pyrometer; with this motion the filament may be set at any angle with the background-image. Vertical motion of the lamp is obtained by turning the knurled head *F*. This turning actuates the screw *W* in the nut *U* which is attached to the center-post supporting the table *T*. With these horizontal and vertical motions it is possible to set the kink of the pyrometer-lamp filament in the optical axis of the instrument.

The bed of the pyrometer is made of a piece of angleiron 2 inches wide by 3 inches high by 8½ feet long. The top and back surfaces (in the picture) are machined. A channel running the full length of the bed at a distance of 3/16 inch from the top, furnishes the place for attaching the hook-clamps, like *B* of figure 7, which hold the lens and telescope standards in position. The clamp *B* is so constructed that, when the thumbscrew is tightened, the clamp not only pulls downward but also exerts a horizontal force which brings the guides, attached to the base of the standard, against the machined surface of the bed; this keeps the parts in alignment. The pyrometer-lamp standard is secured by means of suitable spring-fingers.

To the bed are attached two studs which slide in slots in the top of the piece *Q*, Fig. 8, thus allowing the bed to slide parallel to itself. This motion is produced by turning the knurled hand-wheel *J*, Fig. 7, It permits the operator to focus the pyrometer on the background while he is looking through the telescope. The bed may be locked in place by tightening the thumb-nuts *K*. With the forked rod *G* the observer may make the vertical and horizontal adjustments of the pyrometer-lamp while he views the filament through the telescope. This rod *G* makes the aligning of the parts a simple operation.

The post *L* supports the bed of the pyrometer. It is made of a piece of heavy iron pipe 2¼ inches in diameter which has square threads of ½ cm. pitch on the outside. By turning the nut *M* the bed may be raised or lowered, the maximum range of the motion being 18 inches. The nut may be locked in position by screwing in the handle, thus permitting rotation of the bed about a vertical axis without there being any danger of having the post turn in the nut. From figure 7 it is also seen that the bed may be tilted so that the observer may view the backgrounds either up or down at an angle. These adjustments give the instrument the flexibility which is necessary for general laboratory work. The tripod base is very rigid and stable; it is made of one-inch angleiron bolted to the two cast-iron guides through which the post *L* passes.

The motor with the sectored disc attached is shown at *C*, figure 7. The motor is supported by a laboratory stand which at no point is in contact with the pyrometer. The motor cannot be attached to the pyrometer on account of the vibration which it is almost certain to produce. Some additional sectored-discs are shown in the figure. By using combinations of two discs, sectors having various transmissions can be formed. The writer has used sectors having openings varying from 1° to 230°.

*N* is a Siemens & Halske Precision volt-ammeter, Type 7K. It is equipped with an external adjustable shunt having the following steps: 0.424, 0.322, 0.254, 0.203 and 0.150 ohms. The internal resistance of the meter is 10 ohms and it requires 0.0045 ampere to produce a deflection of 150 scale-divisions. This ammeter with shunt was calibrated at 80, 100, 120 and 140 divisions for each shunt-step by using a standard resistance with a Leeds & Northrup potentiometer. Current values when the pointer is deflected 100 divisions are respectively 0.07319, 0.09623, 0.12033, 0.15044 and 0.20115 ampere.

The pyrometer lamp has a filament about 0.033 mm. in diameter and it requires a current of 0.2350 ampere to match in brightness a black-body at 1828°K. This current causes a deflection of 116.7 divisions when using the fifth shunt; it is the largest current that should be sent through this lamp, since lamps with tungsten filaments will not remain constant for any reasonable length of time if used to match bodies whose brightness-temperatures are greater than 1828°K. The lowest temperature that can conveniently be measured when using the colored glasses is about 1080°K but the curve can be extended down to 975°K by removing the glasses. The current required through the pyrometer lamp when a temperature of 975° is being measured is 0.0818 ampere. The values of the pyrometer-lamp currents given in this paragraph refer to the particular settings of the lens, lamp and telescope shown in figure 7. The aperture of A was U. S. 4 and the discs having apertures of 13 mm. and 15 mm. were used at 1828 and 975° respectively.

In series with pyrometer lamp is the storage battery *O*, the ammeter *N* and the two rheostats *P*. The rheostats are connected in parallel; one has a resistance of 40 ohms and the other a resistance of 107 ohms. A two-volt battery is sufficient when measuring the lower temperatures but a four-volt one is necessary for most of the range.

With the set-up shown in figure 7 the background is magnified about seven diameters. Very often such large magnification is not desirable. With the instrument here described, much smaller magnifications can be used if the lamp and lens are moved closer together. The telescope must then be placed at such a distance from the lamp that the filament may be seen distinctly. If the background is large it will be found very convenient to use a lamp having a filament larger than 0.033 mm.; one of twice this diameter is very commonly used in practice. For each setting of the lens, lamp and telescope, a calibration will be required.

Millimeter profile paper was used for plotting the calibration curves. For the ammeter curves the writer found that a scale of 0.0002 ampere per mm. for the current and 0.2 division per mm. for the deflection, gave current-deflection curves from which currents could be read with an error of less than 0.0001 ampere. The pyrometer-lamp current-temperature curves were drawn to a scale of 0.0002 ampere per mm. for the current and 2° per mm. for the temperature; this was sufficiently accurate for the needs of the writer. Degrees-correction plotted as a function of the observed brightness-temperature gave a useful curve because the observations were made through an absorbing medium. Since a large number of temperature determinations of the same substance were made, a curve connecting brightness-temperature and true-temperature saved much laborious calculation. The slope of the pyrometer-lamp curve changed from point to point. For the set-up of figure 7 it was such that, in the neighborhood of 1000°K, a change of one milliampere in the current through the lamp represented a change of 13° in the temperature of the background; at 1100° the variation was 9° per milliampere; at 1700° the rate of change was 3° per milliampere.

The writer in conclusion wishes to thank the Physics Department for placing at his command such good workshop facilities; Professor L. P. Sieg, under whose supervision the work was done, for his keen interest; Mr. J. B. Dempster for much valuable information regarding workshop methods; and Dr. A. G. Worthing of the Nela Research Laboratory for many valuable suggestions concerning optical pyrometry and for furnishing the calibrated standard-lamp and a pyrometer-lamp.

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