made into a telescope, following, in part, suggestions given to Morse by Waidner and Burgess.

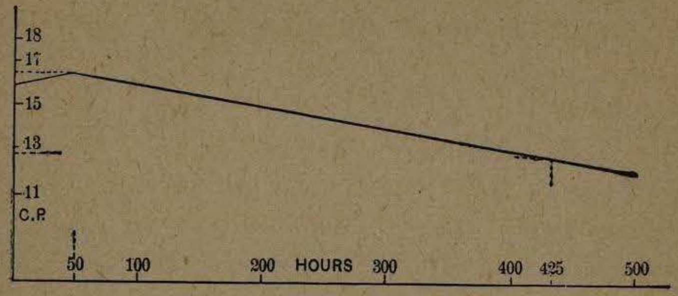

Fig. 118. Behavior of Carbon Lamp.

Henning's Spectral Pyrometer. — In order to eliminate the uncertainties and corrections for the lack of monochromatism of colored glasses used with the Holborn-Kurlbaum instrument, and to permit temperature measurements with any colored light, Henning has devised a spectral pyrometer suitable for exact work in the laboratory from 1000° C. It is essentially a combination of the Holborn-Kurlbaum instrument with a spectrometer as shown in Fig. 119. The collimator KL_2, telescope FL_1, carrying an observing slit D or an ocular, and Abbé prism P which can be set to give any wave length by means of the micrometer MNA, together with the slit E adjustable in width by the screw U, constitute the spectrometer. An image of the incandescent body is superposed on the lamp G by the lens L_4, and both are seen in colored light with the observer's eye before D. The screen B carries a series of suitable stops. The micrometer scale A is calibrated in wave lengths by means of light from standard sources, as helium and mercury vacuum tubes. The instrument may also be arranged for use as a spectrophotometer.

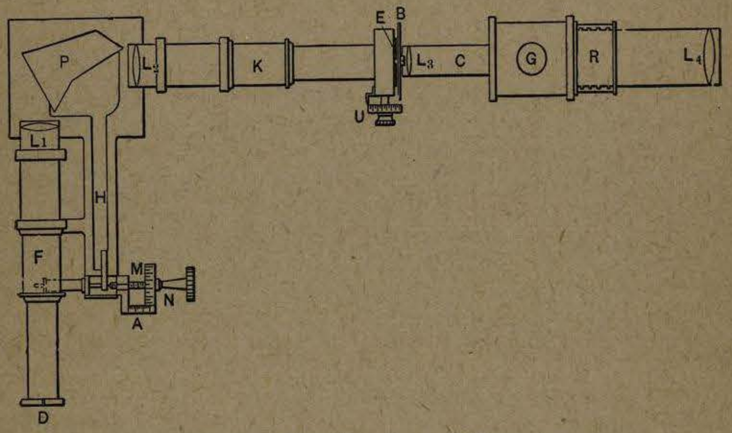

Fig. 119. Henning's Spectral Pyrometer.

Henning has used his spectral pyrometer in a study of metal-filament lamps and for the determination of absorption and reflecting coefficients of metals. He has shown that, for a series of metals, the equation $\frac{1}{S} - \frac{1}{S_0} = \text{const.}$, in which S and S_0 are the absolute black-body temperatures for wave lengths λ and λ_0, holds over a wide range of temperatures; and that the absorption coefficients remain practically constant with change of temperature.

Calibration of Optical Pyrometers. — We have already called attention to the fact that the most accurate method of calibrating an optical pyrometer to about 1600° C. is to take its readings when sighted into an experimental black body (page 239) whose temperature is best given by two or more thermocouples which have in turn been calibrated by determining their E.M.F.'s at the freezing points of three or more pure metals. These calibrations are, in general, best left to a properly equipped standardizing laboratory. However, it is often desirable to be able to calibrate, at least approximately, one's own optical pyrometer, even if not in the possession of a complete standardizing equipment.

A fair substitute for the black body is a resistance-tube furnace of the Heræus type with a diaphragm, say a piece of graphite, inserted at its center, or a little back of this, and on which the optical pyrometer is sighted. The temperature of this diaphragm may be obtained with a calibrated thermocouple or optical pyrometer. Sighted into such a furnace, whose total length is some twenty or thirty times its diameter, an optical pyrometer will read some 5° to 15° C. too low.

The following method may also be used, and this requires no auxiliary pyrometer, but does require from one to three or more deep crucibles of substances of known melting points, preferably the pure metals, such as Al or Sb, Cu, Ni, or Fe. The optical pyrometer is sighted on the bottom of a porcelain tube, preferably blackened inside, and which is thrust into the melted metal, and the reading of the pyrometer taken at the freezing point of the metal.

Where several optical pyrometers are in use in the same establishment, it is well to have at least one of them calibrated carefully and kept as a standard. The others are readily calibrated by comparing their readings with that of the standard when sighted on any convenient incandescent source whatever, provided the pyrometers all use the same colored light; otherwise it is safer to use a furnace as source, although graphite or iron (oxide) will answer in most cases.

The criterium of a satisfactory comparison source for pyrometers using different colors is to view the source, when this is possible, with different colored glasses applied in succession to one pyrometer. If the same reading is obtained for all — red, yellow, and green, for example — the source is satisfactory.

The Wide-filament Comparison Lamp. — A very convenient and rapid method of standardizing one optical instrument in terms of another is shown in Fig. 120, which was devised by Waidner and Burgess for the determination of incandescent lamp filament temperatures and the melting points of very refractory metals. Fig. 120 illustrates the use of a carbon strip *C* mounted in vacuo for the former purpose. The standard pyrometer *L* and the lamp *F* whose filament temperature is sought are both brought to the same brightness as *C*, and the currents in *L* and *F* give a measure of their temperatures, which are assumed equal if the color of the glass *G* is the same as that used before *L* and if the filaments *F* and *L* are of the same material. The lenses *E* and *O* make the readings of *F* more convenient and equalize the two optical systems. Evidently any type of optical pyrometer may be substituted for the lamp *F* and calibrated in a similar manner.

These carbon-strip comparison lamps may be used intermittently to temperatures as high as 1800° C. or even 2000° C. If used only at comparatively low temperatures, they may themselves be calibrated in terms of current *vs.* temperature and then serve as a secondary standard, replacing the black body. Such lamps of this type as are at present available change pretty rapidly with even short burning, so that it is better to keep a filament lamp or other optical pyrometer as the standard and use the wide strips merely as comparison sources. For extending such comparisons to higher temperatures, it would be desirable to replace the carbon with tungsten strips, when probably 2500° C. or more could be realized.

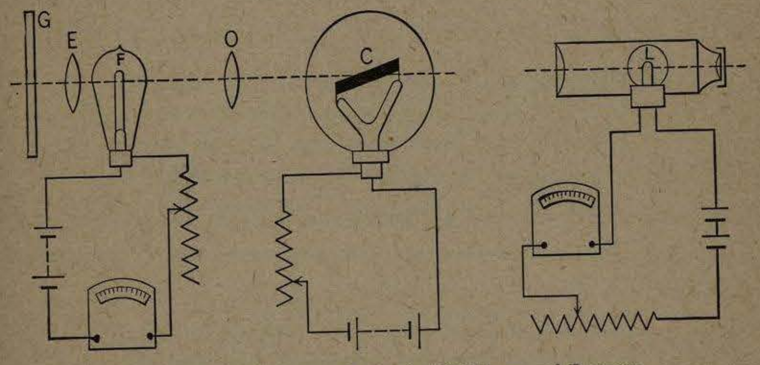

Fig. 120. Calibrating Method of Waidner and Burgess.

Other comparison sources are available, however, for these very high temperatures, such as the Arsem vacuum furnace (Fig. 176) with which temperatures of nearly 3000° C. may be attained, and, moreover, black-body conditions are completely realized.

Use of Wedge-shaped Cavities. — We have already seen that in the calibration of his optical pyrometer Le Chatelier took advantage of crevices in heated materials surrounding a thermocouple to obtain approximately black-body conditions. Féry has called attention to the necessity of the measuring instrument also being black in the Kirchhoff sense, at least when absolute measurements are made, and he developed the use of conical receivers.

Mendenhall, studying the relation between true and apparent temperatures of metals by means of the optical pyrometer, shows that if a thin metal strip is bent into a wedge of small angle, the radiation from within the wedge, heated electrically, as is a lamp filament, is very nearly that of a black body; so that simultaneous readings with a calibrated pyrometer on the outside and inside of such a wedge give a measure of the selective properties of its substance. The wedge may also replace the black body for the comparison of one optical pyrometer with another. Assuming specular reflection and the wedge angle L, the number of reflections perpendicular to the edge of the wedge is $n = \frac{180}{L}$; if the reflecting power of its material is r, that of the wedge is r^n. For many metals r is of the order of 0.7 for red light, when for a 10-degrees wedge $r^n = 0.0016$ and $e = a\epsilon = 0.998\ \epsilon$, corresponding to a temperature difference from a black body of the same brightness of only 0.5° C. at 1600°. For matt surfaces the departure from blackness is greater. The difference in temperature between the inner and outer surfaces of the wedge is less than 1° C. for metals of 0.04 mm. or less in thickness. By burning out such wedges of platinum, Mendenhall and Faryther obtained a value for the platinum melting point only 8 degrees lower than the figure of Waidner and Burgess (1753° C.).

Monochromatic Glasses. — In order to use Wien's law with exactness and convenience, and especially when extrapolation on the temperature scale is resorted to, it is highly desirable that there be no change in the color of the light used in an optical pyrometer. With those pyrometers in which the monochromatic light is produced by means of colored glasses, there may be an error introduced due to the lack of homogeneity of the light transmitted and to the consequent shift with temperature in the position of maximum intensity of the light. For such inhomogeneous glasses this is equivalent to introducing a continuous change of wave length with temperature in Wien's law (page 251).

The behavior of certain Jena glasses, which are among the best in the smallness of this effect, as found by Waidner and Burgess, is shown in the following table:

MONOCHROMATISM OF COLORED GLASSES (JENA).

Glass.	Thickness in mm.	Temperature of source (C).	$\lambda_{max.}$	Limits of transmission band.
Red, No. 2745	3.04	1000	0.645μ	0.698μ–0.610μ
		1250	.650	.731 – .602
		1450	.656	.772 – .598
Red, No. 2745	6.05	1450	.661	.753 – .608
Green, No. 431^{III}	6.18	1150	.547	.602 – .532
		1450	.546	.631 – .468
Blue, No. 3086	4.32	1320	.462	.500 – .421
		1470	.462	.511 – .408

The position of the optical center of gravity ($\lambda_{max.}$ in the table) is seen to remain stationary for the green and blue, but to shift slightly to longer wave lengths for the red glass, with increase in temperature. An error of 0.005μ in the estimation of the equivalent wave length for a colored glass corresponds to an error in temperature estimation of about 5° C. at 1750° C.

For some of the newer monochromatic Jena glasses the following data on the transmission coefficients have been issued by Schott and Genossen:

TRANSMISSION COEFFICIENTS (D) OF JENA GLASSES FOR 1 MM. THICKNESS.

Glass.		Fraction transmitted for wave lengths (in μ).					
Type.	Name.	λ=0.644	0.578	0.546	0.509	0.480	0.436
F 4512	Red filter	0.94	0.05	......	......	......	......
F 2745	Copper-ruby	0.72	0.39	0.47	0.47	0.45	0.43
F 4313	Yellow glass, dark	0.98	0.97	0.93	0.83	0.09	......
F 4351	Yellow glass, medium	0.98	0.97	0.96	0.93	0.44	0.15
F 4937	Yellow glass, light	1.00	1.00	1.00	0.99	0.74	0.40
F 4930	Green filter	0.17	0.50	0.64	0.62	0.44	......
F 3875	Blue filter	......	......	......	0.18	0.50	0.73
F 3815	Neutral black	0.35*	0.35*	0.37*	0.35*	0.34*	0.30*

* For a thickness of 0.1 mm.

The fractional transmission D_x for any other glass thickness x_x is given by the expression $D_x = D^x$, where D is the transmission for 1 mm. as given in the table.

Extension of Scale. — All of the optical pyrometers based on the use of a single wave length, such as the Le Chatelier, Wanner, and Morse, may have their scales indefinitely extended by the use of neutral absorbing glasses (such as Jena Rauch Glas), reflecting mirrors, or prisms of black glass (see Fig. 121), or sectored disks, placed between the furnace, or other source whose temperature is to be measured, and the pyrometer.

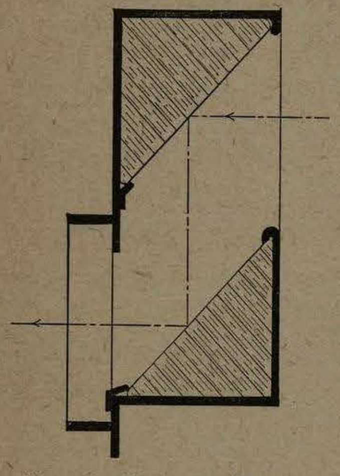

Fig. 121. Absorption Mirrors.

The same principle for the computing of temperatures with the screen in place applies for all of these screens and for any of these pyrometers. It is only necessary to find the *absorption coefficient* of the screen for the colored light used with the pyrometer. This absorption coefficient may be calculated by making use of Wien's law (page 251) and from observations at one or more temperatures. Thus, if K is the absorption factor, that is, the reciprocal of the absorption coefficient, T_1 and T_2 the apparent temperatures in degrees absolute given by the pyrometer, sighting on a black body first without and then with the absorbing screen, then Wien's law III gives

$$\log_{10} K = \log \frac{I_1}{I_2} = \frac{c_2 \log \epsilon}{\lambda}\left(\frac{1}{T_2} - \frac{1}{T_1}\right),$$

when $c_2 = 14{,}500$ for a black body, and λ is the wave length in μ (= 0.001 mm.) of the light used by the pyrometer. Applied to the high-range Wanner and Henning spectral pyrometers, the above formula applies exactly to the highest attainable temperatures if the absorbing screen has a constant coefficient for all brightnesses; but for those pyrometers using colored glasses, which are never strictly monochromatic, there will be an error entering into the extrapolations, which can, however, for the most part, be eliminated by the calibration in wave length *vs.* temperature of the colored glasses used, as shown in the preceding paragraph.

That these corrections can be made satisfactorily is shown by the following from the data of Waidner and Burgess on the determination of the melting point of platinum by means of a Holborn-Kurlbaum pyrometer using red, green, and blue glasses and provided with different kinds of absorbing screens. The metals were melted in an iridium-tube furnace approximating very closely a black body. The observations of Nernst and Wartenberg with a Wanner pyrometer using yellow light are also included, for comparison, their results being reduced to the same optical basis, i.e., for $c_2 = 14{,}500$ in Wien's formula. Measurements by the same observers on palladium gave equally concordant results.

ELIMINATION OF CORRECTIONS TO OPTICAL PYROMETERS.

Observers.	Absorbing screen.	Absorption factor.	Wave length.	Number of observations.	Melting point of platinum.
Waidner and Burgess....	Reflecting mirrors.........	199	0.668	23	1753° ±3 C.
	Reflecting mirrors.........	228	0.547	7	1751 ±3
	Sector disk......	35.4	0.668	10	1753 ±2
	Sector disk......	35.4	0.547	6	1748 ±2
	Sector disk......	35.4	0.462	4	1749 ±3
Nernst and Wartenberg.	Rauch glass.....	147	0.5896	4	1750 ±5

For most materials heretofore used as absorbing screens, either of the mirror or transmitting glass type, there is a rapid variation in absorbing factor with wave length of the incident light (see page 335 and above table). Schott and Genossen of Jena now furnish a "neutral black" glass (F 3815) of an absorbing factor which remains very constant throughout the visible spectrum. The fractional transmission for this glass is given in the table on page 333.

The use of a sector disk is preferable for exact work in the laboratory where the intensity of the source observed has to be cut down, for this form of screen has a constant absorption factor which may be determined geometrically with great exactness. The absorbing glasses are usually more convenient to use than the reflecting mirrors and are equally as good, or better.

Some Scientific Applications. — Our knowledge of phenomena occurring at very high temperatures has been increased greatly in the past few years, largely due to the availability of convenient and precise optical pyrometers using monochromatic light. We shall pass briefly in review some of the uses to which this type of instrument has been put in the laboratory as illustrations of what may be accomplished in high-temperature measurements by optical means.

Temperature of Flames. — Any substance inserted in a flame will take up a lower temperature than that of the flame itself, due to conduction, radiation, and diminished speed of the gas stream around the body. E. L. Nichols, by using thermocouples of progressively finer wires, sought to determine true flame temperatures by extrapolating for a wire of zero diameter. The uncertainty of this method is considerable, although it gives consistent results, which are probably low.

The radiation methods have been employed by several experimenters. The temperature as given by an optical pyrometer will depend on the thickness and density of the flame as well as upon its reflecting and absorbing powers. The reflecting power of a flame is small and probably varies with the kind of flame; the results as yet obtained are quite discordant on this point.

Kurlbaum interposed a flame between a black body and the eye and assumed that the two were of the same temperature when the flame disappeared against its background. This method gave results lower than those obtained by Lummer and Pringsheim (page 252). Kurlbaum and Stewart both claim that the carbon in the flame departs more widely from a black body than platinum, and the latter gets 2282 for the value of A in Wien's displacement equation $\lambda_m T = A$, assuming Nichols's value 1900° C. for the acetylene temperature. Féry has shown, however, that the brightness of the sodium line, measured with a spectrophotometer, is not increased by passing obliquely a beam from an electric light across the flame studied, seeming to indicate that the diffusing power is nil for the light coming from carbon. This would imply a value of A of the order of 2800, or of 2400° C. for the acetylene flame, assuming $\lambda_m = 1.05$.

Féry's method of measuring flame temperatures is to produce the reversal of a metallic line by means of light emitted by a solid body brought to the proper temperature. The image of the filament of an incandescent lamp is thrown by a large-aperture lens onto the narrow slit of a spectroscope. The rays from the filament pass through the flame to be studied, which contains sodium or other metallic vapor. When the filament is raised in temperature the D line, say, is ultimately reversed, and at the moment of disappearance the filament and flame are assumed to have the same temperature, which may be measured by sighting an optical pyrometer on the filament.

Some of Féry's results are as follows:

Bunsen	Open	1870° C.
	Half-open	1810
	Shut	1710
Acetylene		2550
Oxyhydrogen with illuminating gas and oxygen		2200
Oxyhydrogen with $H_2 + O$		2420

For this determination Féry used his absorption pyrometer. The results obtained may be slightly high, but hardly by more than 100° C., as a fine wire of platinum may be melted in an open Bunsen.

There have been other estimations of apparent temperatures of flames by various optical methods based on the radiation laws, some of which have given values greatly below the true temperatures, as measured by the ability of these flames to melt refractory materials of known melting point.