Sources of Error. — A study of a Wanner instrument by Waidner and Burgess has led them to the following conclusions. The sensibility of this pyrometer varies with change in the angle, and is so adjusted as to be the greatest between 1000° and 1500° C., and is about as follows:

0.1 scale div. ≈ 1° C. at 1000° C.
0.1 scale div. ≈ 2° C. at 1500° C.
0.1 scale div. ≈ 7° C. at 1800° C.

The reproducibility of the brightness of the amyl-acetate flame as viewed through the ground-glass diffusing screen is a measure of the ability of the instrument to repeat its indications. It is very important that this diffusing screen be always placed in exactly the same position relative to the flame and slit S_2, and further, that it be free from dust and finger marks. These requirements can only be satisfactorily met by protecting this screen by a cover glass and providing an adjustment for setting it exactly in place between the flame and slit.

The constancy of the amyl-acetate flame as used with this pyrometer under ordinary conditions of burning is illustrated by the following set of observations, during which the current through the electric comparison lamp was kept rigorously constant by means of a milliammeter and rheostat:

Reading of instrument.	Deviations.
39.9	−0.28
39.9	−0.28
40.1	−0.48
39.9	−0.28
39.1	+0.52
39.2	+0.42
39.8	−0.18
39.0	+0.62
39.6	0.38

This shows that the flame can be relied upon to give an intensity of illumination whose constancy expressed in terms of temperature is 0.5 per cent. Variations in height of the flame, if they do not exceed 2 to 3 mm., together with fluctuations in atmospheric conditions, will not produce errors in temperature estimation exceeding 1 per cent.

The uncertainty of setting the Nicol, due to lack of sensitiveness of the eye to exactly match the two halves of the photometric field, is also about 1 per cent, or slightly better with practice.

The adjustment of the electric lamp to standard intensity at the point on the scale chosen as normal point can be made, when proper care is taken regarding the diffusing screen, to 1 per cent expressed in temperature change. This source of error does not affect relative results in any one series for one setting to the normal point.

The most serious source of error, except when special precautions are taken, is the variation in brightness of the electric comparison lamp due to variation in the current furnished by the three-cell storage battery.

With the 10-ampere-hour battery furnished with the Wanner instrument, after making circuit the electromotive force drops by about 2 per cent in two minutes and then falls off slowly, but nearly recovers the original voltage after remaining on open circuit even for a very short time. When the battery is in good condition the variation in three hours at normal discharge (0.75 ampere) is about 0.08 volt, and somewhat less for the current (0.55 ampere) taken by the lamp; with the battery in poor condition these changes are much accentuated.

The following table illustrates the effect of slight variations in current through the lamp on apparent temperature of the amyl-acetate flame, for the small battery of 10 ampere hours furnished with the instrument. The apparent change in temperature is calculated from the current change:

SMALL BATTERY.

Time. Minutes.	Wanner scale.	Current in amperes.	Per cent change in current.	Apparent change in temperature.
15	31.2	0.5645	....	....
20	31.8	0.5640	0.1	1° C.
27	32.7	0.5550	1.7	10
37	34.6	0.5400	4.3	25
36	Disconnected battery two minutes.			
40	32.5	0.5610	0.6	3
42	31.7	0.5570	1.5	7
45	32.5	0.5560	2.5	15
47	33.1	0.5505	4.1	24

A battery of 75 ampere hours gave similar results.

The above results give abundant evidence of the need of maintaining the current through the lamp quite constant in work of precision. A series of experiments has shown that in the range 1000° to 1500° C. one division on the Wanner scale corresponds to about 0.009 ampere, or 1° C. apparent change in temperature is produced by a fluctuation of 0.0012 ampere through the lamp; hence to obtain a precision of 5° the current must be kept constant to 0.01 of its value. The above table shows that this is by no means effected by using the battery without regulating the current, for even with the battery in the best condition the current increases by 2 per cent in the first eight or nine minutes of discharge and then falls off 1 per cent in the next twenty minutes. The temperature coefficient of the battery would produce only insignificant changes. The table shows further that breaking the circuit and then making it again may cause an apparent temperature change of over 20° C. For work of precision, therefore, it is essential to keep the current constant by means of a milliammeter and rheostat, otherwise uncertainties of over 25° C. will occur in the temperature measurements. These will increase with the battery in poor condition.

Range and Limitations. — The above description of the Wanner pyrometer has shown the great loss of light due to the optical system employed. This prevents measuring temperatures below about 900° C. (1650° F.) with this instrument. There is no method of sighting this pyrometer exactly upon the spot desired, except by trial, as no image of the object examined is formed in the eyepiece, but this inconvenience is in part compensated by not having to focus with varying distance from the object.

There is another limitation which may in certain cases become a serious source of error: light from incandescent surfaces is, in general, polarized, and, as the Wanner instrument is a polarizing pyrometer, care must be taken to eliminate this source of error when it exists.

If an incandescent object is viewed normally, the amount of polarized light is very small, but, as the angle of incidence increases, the proportion of light polarized becomes greater and greater. Besides varying with the angle of incidence, the amount of polarized light emitted varies widely with different substances, being greatest for polished platinum and very much less for iron, glass, etc. In some measurements made with the Wanner pyrometer on the temperature of an incandescent platinum strip in the neighborhood of 1350° C., Waidner and Burgess have found a maximum difference in the readings of 90° C. for positions of the instrument at right angles to one another in azimuth and for an angle of incidence of 70° with the normal to the surface. This introduces, under these conditions, the possibility of an error of 45° C. in the temperature measurement. This source of error can be eliminated by taking the mean of four readings for azimuths 90° apart. The magnitude of the error arising from this cause is entirely negligible for all practical purposes for many substances, such as iron, porcelain, etc. A considerable area is needed to sight upon with this pyrometer, which is a disadvantage when small objects are viewed from a distance.

Due to the relatively large surface required in sighting the Wanner pyrometer, there is a tendency to bring the instrument too close to the furnace or object viewed, and this practice carried to excess may readily damage the instrument, deranging its optical parts and altering the calibration by very considerable amounts. Warning of overheating is sometimes given by the change in color of the field. Placing a water jacket between the furnace and instrument or otherwise screening the latter will evidently obviate this difficulty.

Where an attempt is made to sight on very small or distant areas, such as wires or narrow strips which fill only a small part of the photometric field, there may be produced diffraction effects, as noticed by Hartmann.

A review of the sources of error and limitations of the Wanner pyrometer shows that they may exert a relatively great effect on the temperature measurements, and it was, therefore, thought worth while to emphasize them; but, on the other hand, they may all be practically eliminated with reasonable care, and the instrument then becomes one of great precision and convenience, for those measurements for which it is adapted. We shall see later how its range may be extended to the highest temperatures.

Instrument for Low Temperatures. — In order to render his pyrometer available for temperatures below 900°, Wanner has brought out a modification suitable for use from 625° to 1000°, with two ranges, 625° to 800° and 800° to 1000° C., which gives a very open scale and renders the instrument available for a great many industrial operations that were hitherto inaccessible to it. In this low-temperature form, shown in Fig. 116, the light from

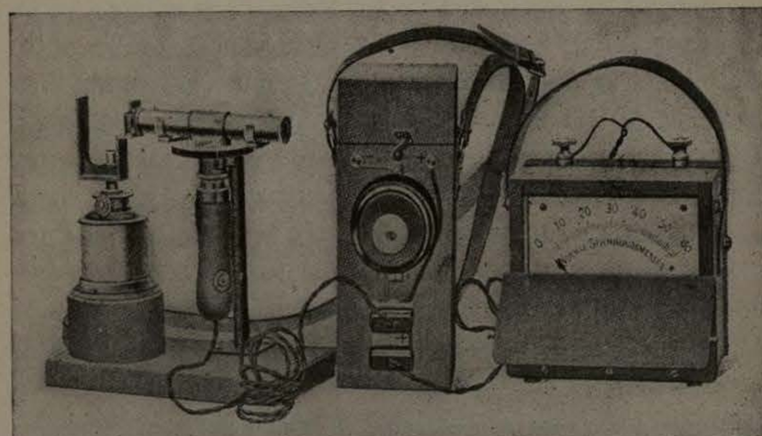

Fig. 116. Wanner Outfit for Low Temperatures.

the furnace does not pass through the polarizing system, and the direct-vision prism is replaced by a red glass in the eyepiece, by which elimination light of much feebler intensity than with the high-range apparatus can be observed. The apparatus is very compact and easy to manipulate. It requires as accessories a 4-volt storage battery, milliammeter, and amyl-acetate standard.

Holborn-Kurlbaum and Morse Pyrometers. — If a sufficient current is sent through the filament of an electric lamp, the filament glows red at first, and as the current is increased the filament, getting hotter and hotter, becomes orange, yellow, and white, just as any progressively heated body. If now this filament is interposed between the eye and an incandescent

object, the current through the lamp may be adjusted until a portion of the filament is of the same color and brightness as the object. When this occurs this part of the filament becomes invisible against the bright background, and the current then becomes a measure of the temperature as given either by a thermocouple or in terms of the intensity of illumination. This principle appears to have been first used by Morse and independently developed by Holborn and Kurlbaum. An absolute match of both color and brightness cannot be made unless monochromatic light is used or unless the lamp filament and viewed object radiate similarly.

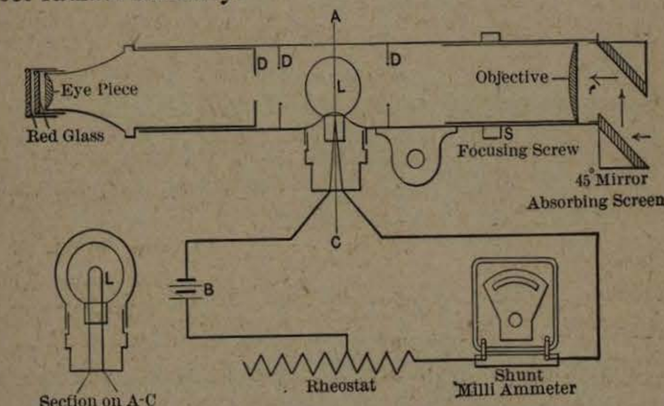

Fig. 117. Holborn-Kurlbaum Pyrometer.

Holborn-Kurlbaum Form. — A small 4-volt electric incandescent lamp L with a horseshoe filament is mounted in the focal plane of the objective and of the eyepiece of a telescope provided with suitable stops D, D, D, and a focusing screw S for the objective. The lamp circuit is completed through a two-cell storage battery B, a rheostat, and a milliammeter.

The determination of a temperature consists in focusing the instrument upon the incandescent object, thus bringing its image into the plane AC, and adjusting the current by means of the rheostat until the tip of the lamp filament disappears against the bright background, when a previous calibration of current, in terms of temperature for the particular lamp used, gives the temperature by reading the milliammeter.

As the temperature of the filament increases, the effect of irradiation or too great brightness becomes blinding, and the photometric comparison is then rendered possible at these temperatures by the introduction of one or more monochromatic red glasses before the eyepiece, giving as well all the advantages of photometry of a single color. Below 800° C. the measurements are more easily made without any red glass, as the filament itself is then red, and the lowest temperatures are, of course, reached with the least interposition possible of absorbing media. The lower limit of the instrument is very nearly 600° C. Two red glasses are required for temperatures above 1200° C., and for very high temperatures, above 1500° or 1600° C., it is necessary, in order to avoid overheating the lamp filament by the current, to put absorbing glasses or a double-prism mirror (Fig. 121) before the objective; and they also, of course, require calibration. At very high temperatures, unless a strictly monochromatic glass is used, the pyrometry becomes difficult, the filament never disappearing completely.

The eye is particularly sensitive in recognizing equality of brightness of two surfaces, one in front of the other, and this pyrometer, therefore, provides a very delicate means of judging temperatures, since the light intensity, as has been shown (page 238), varies so much faster than does the temperature.

The precision attainable with this pyrometer is illustrated by the following series of observations which are indicative of the ordinary performance of the instrument:

Temperature from H.-K. pyrometer.	Temperature from thermocouple.	Temperature from H.-K. pyrometer.	Temperature from thermocouple.
1347	1347° C.	632	634° C.
1351	1347	634	633
1343	1343	633	633
1333	1332	633	632
1342	1342		

Different observers do not differ by any appreciable amount in their readings, and at low temperatures the same values are obtained whether a red glass is used or not.

For the calibration of the instrument, it is necessary to find empirically the relation between the current through the lamp and the temperatures for a number of temperatures, and then interpolate either analytically, or more conveniently, graphically. The calibration will evidently be an independent one for each lamp used.

The relation between current and temperature is sufficiently well expressed by a quadratic formula of the form

$$C = a + bt + ct^2.$$

That this formula gives satisfactory results is shown by observations of Holborn and Kurlbaum for a lamp satisfying the equation

$$C\,10^3 = 170.0 + 0.1600\,t + 0.0001333\,t^2,$$

when sighted on a black body (page 239), the temperature of which is given by a thermoelectric pyrometer calibrated at known melting points.

C amp. 10^{-3}.	t obs.	t calc.	Δt.
340	686	679	−7° C.
375	778	778	0
402	844	850	+6
477	1026	1032	+6
552	1196	1196	0
631	1354	1354	0
712	1504	1504	0

We may also cite the behavior of one of the several standard pyrometer lamps of the Bureau of Standards. This lamp satisfies the equation

$$C = 0.1681 + 0.0_3\,1482\,t + 0.0_6\,1700\,t^2.$$

C in amps.	t obs.	t calc.	Δt
0.4486	920	921	−1°
.5305	1087.5	1087.5	0
.3357	650	649	+1
.6023	1221	1221	0
.3525	692	692.5	−0.5
.6393	1285	1285	0
.5309	1089	1088.5	+0.5

No appreciable change in the readings of this lamp could be detected over a five-year period, the lamp being used very frequently during that time to temperatures as high as 1500° C.

Pirani and Meyer have shown that, for carbon and metal filament lamps,

$$\log C = a + b \log T$$

where C = current and T = absolute temperature. This permits of a calibration with two temperatures only.

Mendenhall suggests that this pyrometer — and the same is true of all the optical instruments using monochromatic light — may be calibrated for all temperatures in terms of a single known temperature, such as the palladium melting point, by means of a series of sectored disks each of a different aperture, giving, by the application of Wien's law (see page 250), a corresponding series of effective temperatures. The sectors, of some 15 cm. diameter, may be rotated by means of a shaft attached to a small motor fixed near the middle of the outside of the pyrometer tube. Mendenhall has also made a direct-vision spectroscopic eyepiece for this instrument, and works with a field of about 25 A.U. width, giving λ to about one-fifth per cent in the middle of the visible spectrum.

Holborn and Kurlbaum as well as Waidner and Burgess have made a thorough study of the effects of aging.

Lamps which have not been aged or burned for some time at a temperature considerably above that at which they will ordinarily be used, undergo marked changes and are unreliable, but, if properly aged, they reach a steady condition, as indicated by the following table of results obtained by Holborn and Kurlbaum on these lamps. The current is given in each case for a temperature of 1100° C.

AGING OF LAMPS.

	Current.		
Lamp number	1	2	3
After 20 hours burning at 1900° C.	0.608	0.592	0.589
After 5 hours burning at 1900° C.	.613	.592	.592
After 5 hours burning at 1900° C.	.621	.597	.597
After 5 hours burning at 1900° C.	.622	.599	.600
After 20 hours burning at 1500° C.	.622	.599	.601

If a lamp is not aged its indications may change by as much as 25° C. with time, but after twenty hours' heating at 1800° it will undergo no appreciable further changes over a period of time corresponding to many months if used in the shop, if not heated above 1500°. This state of permanence is sufficient to satisfy the most rigid requirements of practice.

By the substitution of tungsten for carbon filaments even greater permanence may be had, but the selective radiation of the metallic filament may then be a source of error or inconvenience in certain cases.

Morse Thermogage. — In its original form, instead of a simple horseshoe filament, Morse used a large spiral filament in the lamp of his pyrometer, so that in sighting upon an incandescent body it was necessary to choose some particular spot of the spiral and try to make that spot disappear. This is fatiguing, as the spiral covers a large area and is of just sufficiently varying intensity to cause the eye to wander. This effect was aggravated by the fact that this instrument was not a telescope, possessing no eyepiece or objective, so that the eye had to accommodate itself back and forth between the filament and the object studied.

Instead of the 4-volt battery for the Holborn-Kurlbaum lamps, the spiral lamp took a battery of 40 or 50 volts, requiring a costly installation unless the fluctuations of the ordinary 110-volt lighting circuit were not too troublesome to use it with a suitable rheostat or shunt.

The Morse instrument was designed for use in hardening steel, and, throughout the limited temperature range required in this process, in spite of the crudities of construction above noted, this pyrometer could be read to about 3° C. within this range. Above 1100° C., however, it is very difficult, and it soon becomes impossible to make a satisfactory setting.

Tests of these spiral filament lamps show that when aged at 1200° C. they will remain constant for several hundreds of hours within the range over which they are intended to be used.

It is interesting in this connection to note the behavior of ordinary carbon incandescent lamps as to permanence. (See Fig. 118.)

Later forms of the Morse thermogage are provided with lower voltage lamps with a single loop, red glass at the eyepiece, and