Making use of Wien's displacement law in form $\lambda_{max} T = 2940$, Ladenburg found 1405° for the Hefner and 1842° for the acetylene flame. Becker, by a spectrophotometric method, obtained 1395° for the Hefner.

Kurlbaum and Schulze, by a method similar to Féry's, found apparent variations in Bunsen flame temperatures when colored with different salts; but E. Bauer, using the same method, showed that by using a definite part of the flame no such differences exist from one salt to another nor from one color to another. For the oxyhydrogen flame Bauer finds 2240° by applying Planck's law, and 2200° to 2300° by the reversal of the *D* line, using an electric arc as source of light in Féry's method. Bauer found from 1660° to 1850° for various portions of the Bunsen flame, using several optical methods.

All of the above methods assume that flames are nonluminescent, otherwise the results obtained are too high. Absurd results will also be obtained if the flames are colorless, i.e., contain no finely divided particles heated by the flame, as in an open Bunsen.

*Temperature of Glow-lamp Filaments.* — Since the observations of Le Chatelier with his optical pyrometer, and of Lummer and Pringsheim making use of the Wien relation $\lambda_m T =$ const., there have been numerous determinations of lamp temperatures by means of optical pyrometers. The first satisfactory observations for a series of lamps were made by Waidner and Burgess in 1906, using their graphite-strip method of comparison (page 330), and the Holborn-Kurlbaum instrument, furnished with red, green, and blue glasses in succession before the eyepiece to enable estimations of true temperature to be made from the apparent temperatures, which last, of course, depend upon the selective radiation of the filament surfaces. They found that for platinum filaments inclosed in an evacuated glass bulb, adding the difference in temperature between the blue and red readings to the apparent temperature with blue light when sighted on the carbon strip, there was given very nearly true temperatures — for example, 1760° C. for the platinum melting point.



Assuming this empirical relation to hold generally, they found the following:

NORMAL BURNING TEMPERATURES OF GLOW LAMPS.

| Type of lamp. | Watts per candle power. | Volts. | Observed black-body temperatures (red). | Maximum true temperature. | Minimum true temperature. |
|---|---|---|---|---|---|
| Carbon........ | 4.0 | 50 | 1710° C. | 1800° C. | 1755° C. |
| Carbon........ | 3.5 | 118 | 1760 | 1850 | 1805 |
| Carbon........ | 3.1 | 118 | 1860 | 1950 | 1905 |
| Tantalum...... | 2.0 | 110 | 1865 | 2000 | 1935 |
| Tungsten...... | 1.0 | 100 | 2135 | 2300 | 2215 |

In some of the other estimations no attempt has been made to correct for the lack of blackness of the filaments, and the results appear to be generally too low. We may cite the following determinations:

NORMAL LAMP TEMPERATURES BY VARIOUS OBSERVERS.

| Observers. | Carbon. | Tantalum. | Tungsten. | Method and remarks. |
|---|---|---|---|---|
| Grau....... | 1660 | .... | 1850 | Iridium strip and Wanner pyrometer. |
| Coblentz... | 1785 | 1910 | 2060 | $\lambda_m T = C$ and graphite "black." |
| | 1570 | 1670 | 1810 | $\lambda_m T = C$ and platinum "black." Temperature obs. of Waidner and Burgess with red light. |
| Féry....... | 1780 | .... | 1875 | Combination of Wien and Stefan laws; assumes W behaves like Pt. Used absorption pyrometer. |
| Pirani...... | .... | 2000 | 2080 | Resistance and optical measurements. |
| Joly ....... | 1650 to 1720 | 1740 | 1810 | Total photometric (Nernst); other methods gave lower values. |

These figures are not strictly comparable, as the ratings are not exactly the same; roughly, they are $W = 1.25 \frac{W}{c.p.}$, $Ta = 1.5 \frac{W}{c.p.}$ and carbon $= 3.5 \frac{W}{c.p.}$.

The use of the equation $\lambda_m T = C$ (Coblentz) is questionable, as the form of the energy curves of lamp filaments is not that of the black body.

The normal burning temperature of the Nernst filament has been measured several times, ranging from the absurdly low result of Hartmann of 1535° obtained with a thermocouple, to the value 2360° of Ingersoll by a luminous-efficiency method. Mendenhall and Ingersoll found that rhodium would melt on a Nernst filament below its normal burning, and that iridium would not, which places this temperature at about 2100° C.; an application of Wien's law gave them 2125° C.

*Temperatures within Furnaces.* — The optical pyrometer, especially in its forms due to Wanner and to Holborn and Kurlbaum, has been of the greatest use in studying very high temperature phenomena, including the formation, modification, and dissociation of many chemical products. Besides the numerous melting-point determinations described elsewhere, we may mention as illustrations the work of Nernst and his associates at Berlin on gaseous dissociation to temperatures above 2000° C., carried out in his type of iridium furnace; of Tucker and others at Columbia University on carborundum and other furnace products; of Thompson at the Mass. Inst. of Technology on a series of chemical reactions; of Greenwood and of Prim at Manchester, using a carbon vacuum and pressure furnace, on boiling points of the metals and on the temperature of formation of many chemical substances. In all of the above investigations the Wanner pyrometer was used, but where the furnace opening is small, as is usually the case, there is advantage in using an instrument requiring only a few millimeters area to sight on, as the Holborn-Kurlbaum type. This has been used at the Reichsanstalt in comparing the optical and gas scales, and at the Bureau of Standards in most of the high-temperature work there, as well as at the Geophysical Laboratory. Using an Arsem furnace (Fig. 176), Dr. Kanolt with this pyrometer has been able to measure melting and freezing points of salts, alloys, and minerals to temperatures above 2100° C. by taking the



heating and cooling curves and making use of the latent heat of transformation. A few tenths of a gram of material are sufficient to give a very sharp point (see Fig. 122).

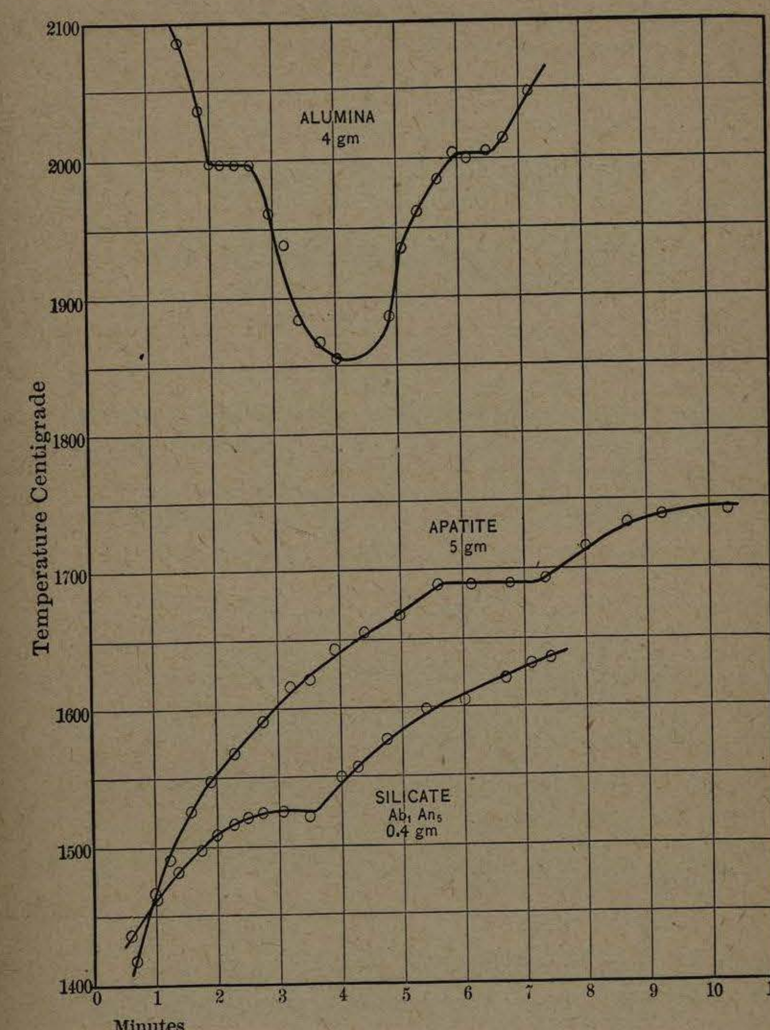


Fig. 122. Melting Points with Optical Pyrometer.

*Melting points of microscopic samples* may also be obtained readily with the Holborn-Kurlbaum pyrometer by making use of the known departure from blackness, or the emissivity, of some substance such as platinum, on a strip of which, or other suitable material such as iridium, carbon, or tungsten, may be placed the substance whose melting point is sought.

In Fig. 123 is shown the apparatus of Burgess used for the determination of the melting of points of the iron group (Chap. XI) in hydrogen, using samples of the order of 0.001 mg. melted on a platinum strip heated by a delicately adjustable electric current. The container is of brass blackened inside, and simultaneous observations are taken through a mica window of the

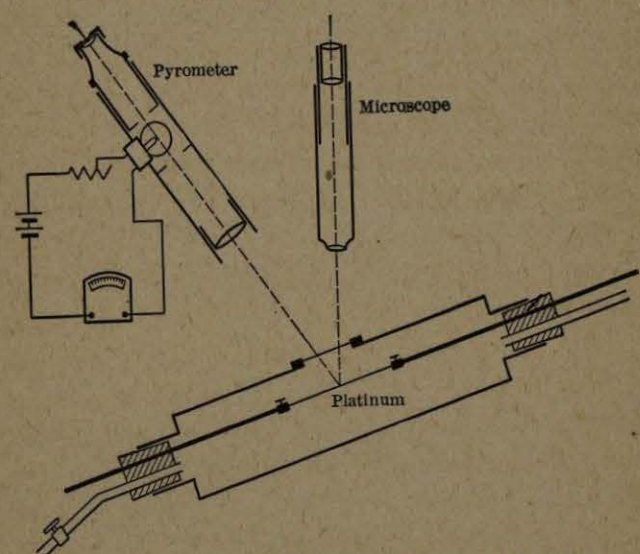


Fig. 123. Apparatus of Burgess for Microscopic Samples.

melting of the sample with a microscope and of the temperature of the strip with the pyrometer.

**Conditions of Use.** — The optical pyrometer using monochromatic light, by reason of the uncertainty of emissive powers and of the relatively slight sensibility of the eye for comparisons of luminous intensities, cannot give quite as accurate results as the electric methods, although the accuracy attainable, since the satisfactory establishment of the laws of radiation throughout practically the attainable temperature range, is sufficient, as we have seen, when proper precautions are taken, for all industrial and most scientific needs. The range of this pyrometer is from about 650° C. to the highest attainable temperature.



The optical or radiation pyrometer is peculiarly well adapted for many cases in which other methods fail, as when contact with the object whose temperature is sought cannot be made or when for any reason the pyrometer must be placed at a distance; for example, in the case of a moving body, as a rail passing into the rolling mill; in the case of very high temperatures, as of the crucible of the blast furnace or that of the electric furnace; in the case of isolated bodies radiating freely into the air, as flames or wires heated by an electric current which cannot be touched without changing their temperature. We have also seen that it may give very exact results in such cases when the emissive properties of the substances sighted upon are known, as is often the case.

It is also convenient in the case of strongly heated furnaces, as steel and porcelain furnaces. But in this usage care must be taken to guard against the brightness of the flames, always hotter than the furnace, and against the entry of cold air. The arrangement with the closed tube described in connection with the heat-radiation pyrometer is advisable if it is desired to obtain the most exact results. The optical pyrometer has the inconvenience to require active intervention on the part of the operator and can hardly be intrusted to a workman without oversight, while the set-up of the heat-radiation pyrometer may be made so that an observation reduces to a reading upon a scale. The latter pyrometer, however, is the more subject to error due to lack of blackness, flames, and furnace gases.

*Some Industrial Uses.* — The several forms of optical pyrometer using monochromatic light have been very generally introduced into industrial practice, where they are rendering most useful service, and for many operations they may advantageously replace the eye of the operator. Practically every furnace operation can be controlled by this type of pyrometer with great precision, with a resulting saving of fuel and a more uniform furnace product. A few of the types of furnaces for which such pyrometers are adapted are the various steel-melting furnaces, blast furnaces, coke ovens, ceramic kilns, and glass weirs. In forging, annealing, hardening, and similar operations on steel, and in foundry practice in general, such pyrometers are equally useful.

We have already called attention (page 305) to some industrial measurements made by Le Chatelier with his optical pyrometer. We may also mention some determinations with the Wanner pyrometer on a battery of six coke ovens:

| Oven. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Over the retorts | 1232 | 1264 | 1370 | 1464 | 1409 | 1436 |
| Just over generator | 1409 | 1397 | 1464 | 1397 | 1296 | 1264 |
| Fifth flue | 1126 | 1002 | 1112 | 1104 | 1096 | 1119 |
| Next to last flue | 992 | 982 | 918 | 932 | 970 | 932 |

The Morse or Holborn-Kurlbaum type may be sighted on distant objects conveniently. It is possible to set up such an instrument in a foundry or forging shop and from one position measure temperatures of several furnaces, of pieces under the hammer, and of metal being poured into and from ladles.

**Measurement of the Relative Intensity of Different Radiations.** — It is on this principle that rests the eye estimation of temperatures such as are made by workmen in industrial works. Numerous attempts, none very successful, have been made to modify this method and make it precise. There is need to consider this mainly from the point of view of a rough control over the heating of industrial furnaces. Recently a modification of this method has been devised by Nordmann, which, as we shall see, is of interest in the estimation of the extremely high temperatures of stars.

*Use of the Eye.* — Pouillet made a comparison of the colors of incandescent bodies in terms of the air thermometer. The table that he drew up is reproduced everywhere to-day:

POUILLET'S COLOR SCALE.

| | | | |
|---|---|---|---|
| First visible red | 525° | Dull orange | 1100° |
| Dull red | 700 | Bright orange | 1200 |
| Turning to cherry | 800 | White | 1300 |
| Cherry proper | 900 | Brilliant white | 1400 |
| Bright cherry | 1000 | Dazzling white | 1500 |



The estimation of these hues is very arbitrary and varies from one person to another; more than that, it varies for the same person with the exterior lighting. The hues are different by day from those by night; it is thus that the gas flame, yellow during the day, appears white at night. It is only in the reds that any accuracy can be had by the eye method. Workmen can sometimes guess to better than 25° C. up to 800° C. At 1200° errors of over 200° will be made.

*Use of Cobalt Glass.* — One may exaggerate the changes of hue in suppressing from the spectrum the central radiations, the yellow and green for example, so as only to keep the red and the blue. The relative variations of two hues are the greater the more separated they are in the spectrum; now, the red and the blue form the two extremities of the visible spectrum.

It has been proposed for this purpose to use cobalt glass, which cuts out the yellow and green, but lets pass the red and blue. It must be remembered that the ratio of the radiations transmitted varies with the thickness of the glass as well as with their absolute intensities.

Let $I_a$ and $I_b$ be the intensities of the radiations emitted, $k_a$ and $k_b$ the proportions transmitted by the glass through a thickness 1. Through a thickness $e$ the proportion transmitted will be

$$\frac{I_a k_a^e}{I_b k_b},$$

which will vary with $e$ in all cases that $k_a$ is different from $k_b$.

It results from this that two cobalt glasses, differing in thickness or in amount of cobalt, will not give the same results. So that if the cobalt glass habitually used is broken, all the training of the eye goes for naught.

Besides, cobalt has the inconvenience of having an insufficient absorbing power for the red, which predominates at the more ordinary temperatures that we make use of. It would be possible, without doubt, by the addition of copper oxide, to augment the absorbing power for the red.

One would have better and more comparable results by employing solutions of metallic salts or of organic compounds suitably chosen. But few trials have been made in this matter.

**Pyroscope of Mesuré and Nouel.** — It is known that by placing between two nicols a plate of quartz cut perpendicularly to the axis, a certain number of the radiations of the spectrum are suppressed. This latter is then composed of dark bands whose spacing depends on the thickness of the quartz and the position of the angle of the nicols. Mesuré and Nouel have utilized this principle in order to cut out the central portions of the spectrum; this solution is excellent and preferable to the use of absorbing media. The apparatus (Fig. 124) consists essentially of a polarizer $P$ and an analyzer $A$, whose adjustment to extinction gives the zero of graduation of the divided circle $CC$. This circle is gradu-

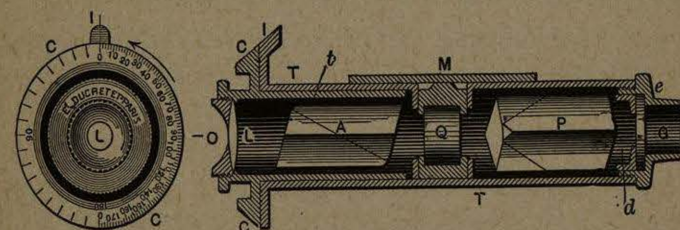


Fig. 124. Apparatus of Mesuré and Nouel.

ated in degrees and is movable before a fixed index $I$. Between the two nicols $P$ and $A$ is a quartz $Q$ of suitable thickness, carefully calibrated. The mounting $M$ allows of its quick removal if it is necessary to verify the adjustment of the nicols $P$ and $A$. The quartz $Q$ is cut perpendicularly to the axis. A lens $L$ views the opposite opening $C$ furnished with a parallel-faced plate glass or, where desired, with a diffusing glass very slightly ground.

The relative proportions of various rays that an incandescent body emits varying with the temperature, it follows that for a given position of the analyzer $A$ the composite tint obtained is different for different temperatures.

If the analyzer is turned while a given luminous body is viewed, it is noticed that the variations of coloration are much more rapid for a certain position of the analyzer. A very slight rota-



tion changes suddenly the color from red to green. Now, if the analyzer is left fixed, a slight variation in the temperature of the incandescent body produces the same effect. The transmission hue red-green constitutes what is called the sensitive hue. There are then two absorptions, one in the yellow and the other in the violet.

This apparatus may be employed in two different ways. First fix permanently the analyzer in a position which gives the sensitive hue for the temperature that is to be watched, and observe the changes of hue which are produced when the temperature varies in one direction or the other from the chosen temperature. This is the ordinary method of use of this instrument. It is desired in a given manufacturing process (steel, glass) to make sure that the temperature of the furnace rests always the same; the instrument is adjusted once for all for this temperature. It suffices to have but a short experience to train the eye to appreciate the direction of the change of hue.

The inventors have sought to make of their apparatus a measuring instrument; this idea is quite open to debate. In theory this is easy; it suffices, instead of having the analyzer fixed, to make it turn just to the securing of the sensitive hue and to note the angle which gives the position of the analyzer. But in fact the sensitive hue is not rigorously determinate and varies with the observer. A graduation made by one observer will not hold for another. It is not even certain that the same observer will choose always the same sensitive hue. At each temperature the sensitive hue is slightly different, and it is impossible to remember throughout the scale of temperatures the hues that were chosen on the day of the graduation. There is even considerable difficulty to recall this for a single temperature.

The following figures will give an idea of the differences which may exist between two observers as to the position of the sensitive hue:

| | Temperature. | Angle of analyzer. (1) | (2) |
|---|---|---|---|
| Sun | 6000° | 84 | 86 |
| Gas flame | 1680 | 65 | 70 |
| Red-hot platinum | 800 | 40 | 45 |