approximately, it is not with overconfidence that any considerable extrapolation of their temperature scales may be resorted to.

If a standard total-radiation instrument can once be calibrated satisfactorily in any laboratory, however, to very high temperatures, it will then be an easy matter to compare with it any other such pyrometers by sighting on any source of radiation whatever with the two instruments simultaneously.

It is perhaps proper to remark that these difficulties of realizing suitable calibration conditions impose equal uncertainties in the indications of such instruments as ordinarily used in practice.

The computation of a calibration is readily made by graphical methods. The equation $E = aT^n$, in which E is the E.M.F. generated for the absolute temperature T of a black body, and a and n are constants, represents well enough for most purposes the behavior of thermoelectric instruments of the Féry type. Plotting log E against log T gives us a straight line, so that only two points are absolutely necessary for calibration if the scale of E is correct and a strictly potential scale of E.M.F.'s. When a diaphragm is used for getting the higher temperatures, one observation combined with the two previous ones will suffice theoretically, as this second straight line should be parallel to the first. In practice this is very nearly but apparently not quite the case, due to extraneous heating and differences in behavior with the diaphragm in place and removed, so that there is some element of uncertainty in extrapolating by the above procedure.

Pyrometric telescopes may be most accurately calibrated by the potentiometric method (p. 135), when their readings are independent of the resistances of thermocouple circuit and galvanometer.

CHAPTER VIII.

OPTICAL PYROMETER.

Principle. — Instead of using the totality of the radiant energy, as in the methods described in the preceding chapter, use is made of the luminous radiations only. This utilization may be effected in many different ways, which give methods of unequal precision and varying in facility of manipulation.

Before beginning their study, it may be well to recall and illustrate certain properties of monochromatic radiation.

Properties of Monochromatic Radiation.—An incandescent body emits radiations of different wave lengths. For a given wave length and a given temperature, the intensity of this emitted radiation is not the same for different bodies: this is expressed by saying that they have for this radiation different *emissive powers*. Similarly, a body which receives radiations of a given wave length absorbs a part of them and sends back another part by diffusion or reflection; a certain quantity may also traverse the body. The *diffusing*, *reflecting*, or *transmitting* power at a given temperature, for a given wave length, varies from one body to another. The *emissive power and the diffusive power* (in the case of an opaque and nonreflecting body) *vary always inversely, resting complementary to each other.*

Substances of great emissive power, as lampblack, have a small diffusive power; substances of small emissive power, as polished silver and magnesia, have a very great diffusing or reflecting power.

If we take as the measure of the emissive power the ratio of the intensity of the radiation of the object considered to that of a black body (page 239) at the same temperature, and as measure of the diffusive power the ratio of the intensity of the radiation diffused to the incident radiation, the sum of these two quantities is equal to unity (see page 243).

The emissive power of a body varies from one radiation to another, and consequently also its diffusing and transmitting powers, since these two powers are complementary to each other. It follows that the relative proportions of the visible radiations received or given off by a body are not the same; so that different bodies, at the same temperature, appear to us to be differently colored.

At the same temperature, the color proper to a body, and its apparent color when it is lighted by white light, are complementary to each other. Yellow substances, as oxide of zinc heated, emit a greenish-blue light. At temperatures less than 2000° the red radiations predominate greatly and mask the inequalities of the radiations of other wave lengths. To render easily visible the colorations of radiating bodies, it is necessary to compare them with those of a black body under the same temperature conditions. A hole pierced in the body, or a crack across the surface, gives a very good term of comparison to judge of this coloration.

The intensity of the radiations emitted by a black body increases always with the temperature, and the more rapidly as we approach the blue region of the spectrum; but, on the other hand, the radiations from the red end are the first to commence to have an intensity appreciable to vision, so that the color of bodies heated to higher and higher temperatures starts with red, tending towards white, passing through orange and yellow. White is, in fact, the color proper to bodies extremely hot, as is the sun.

Bodies not black (the word "black" always being used in the sense of Chapter VI, page 239) have a law of increase different from that for black bodies, because the emissive power varies with the temperature. It increases unequally for the various radiations, so that the color of bodies, with respect to the color of a black body, changes with the temperature.

The following table gives for different colors the ratios of the values of emissive powers of some bodies to that of a black body as determined by Le Chatelier. The red radiation was observed through a glass containing copper, the green by aid of a chro-

mium copper glass, the blue through an ammoniacal solution of cupric hydrate. The substance covered the junction of a thermoelectric couple, and was cut by grooves; and it was the brightness of the bottom of these grooves which was compared to that of the surface.

EMISSIVITIES (LE CHATELIER).

		Red.	Green.	Blue.
Magnesia	at 1300°	0.10	0.15	0.20
	1550	.30	.35	.40
Lime	1200	.05	.10	.10
	1700	.60	.40	.60
Oxide of chromium	1200	1.00	1.00	1.00
	1700	1.00	.40	.30
Oxide of thorium	1200	.50	.50	.70
	1760	.60	.50	.35
Oxide of cerium	1200	.80	1.00	1.00
	1700	.90	.90	.85
Auer mixture	1200	.25	.40	1.00
	1700	.50	.80	1.00

Values of the emissivities of metals and other substances are given in Table X of the Appendix.

Methods of Temperature Measurement. — The estimation of temperature, from measurements of luminous radiations, may, at least in theory, be made directly in three different ways, by utilizing:

The total intensity of the luminous radiation;
The intensity of a radiation of definite wave length;
The relative intensity of radiations of definite wave lengths.

In the chapter (VI) on the laws of radiation we have discussed the recent theoretical and experimental advances underlying these methods.

Measurement of Total Luminous Intensity. — The brightness of substances increases very rapidly with the temperature. One may with the unaided eye estimate comparatively this brightness, but this measurement is very uncertain, for lack of a constant standard of comparison. The sensitiveness of the eye varies, in fact, with the individual, with the light which the eye received immediately preceding, and with the attendant fatigue. Photometric processes, precise for comparison with a standard source, cannot be employed on account of the change of hue with the temperature.

The following method might be tried: Trace on a white surface, diffusive or translucent marks, of definite intensity and dimensions, and seek what fraction of the light must be employed to render the marks invisible. The indications will be still quite variable and will depend upon the degree of the eye's fatigue.

Nernst and others have made use of the empirical formula (A) of page 238,

$$\frac{I_1}{I_2} = \left(\frac{T_1}{T_2}\right)^x, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A)$$

connecting the total photometric brightness, expressed, for example, in Hefner candles, of a radiating body and its temperature. Rasch deduces theoretically the more general formula

$$I = I_1 \epsilon^{\alpha\left(1 - \frac{\theta}{T}\right)}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (B)$$

in which θ is the absolute temperature for which $I = I_1$. If I_1 is the brightness of the Hefner standard, we have per $\overline{\text{mm.}}^2$ of the luminous radiation from a black body, $\alpha = 12.94$ and $\theta = 2068$ abs. For small temperature differences (B) reduces to (A) if $xT =$ const. In view of the fact that several investigations involving considerable temperature differences have been based on the use of (A), it should be emphasized that (A) does not hold unless T_1 is very nearly equal to T_2.

Using (A) and taking the light from 1 $\overline{\text{mm.}}^2$ from a black body = 12.1 Hefners, when the two are of equal total photometric brightness, Nernst finds for the melting point of platinum 1782° and of iridium 2200° to 2240° C. Rasch, treating Nernst's data by (B) gets for iridium 2287° C. The same formulæ, it is interesting to note, apply also to monochromatic light, which amounts to saying that (A) and (B) used for total light give relations equivalent quantitatively, as shown by Rasch, to Wien's law for $\lambda = 0.542$, or approximately for the wave length of maximum sensibility of the eye, which is not a strictly constant

quantity for different individuals nor for the same individual at different times. See page 255 and Fig. 88.

This method of using the total photometric brightness as a measure of temperature, therefore, lacks sensitiveness as well as definiteness, and is better replaced by methods based on the use of a single wave length.

Measurement of the Intensity of a Simple Radiation. — We may estimate the temperature of a body from the intensity of one of its radiations, provided that we know the emissive power of the body at that temperature and the law of variation of this radiation determined in terms of the gas thermometer.

The emissive power sometimes varies with the temperature, and generally is not known. It might seem that this would be enough to reject this method and similar methods by radiation. But this is not so, for the following reasons:

1. At temperatures higher than the fusing point of platinum there is no other pyrometric method at present applicable.

2. A great many substances have a considerable emissive power, nearly unity, and particularly some of industrial importance, as iron and coal.

3. The variation of radiation with temperature is sufficiently marked so that the errors committed in neglecting the emissive power are small. Thus at 1000° the red radiation emitted by carbon is quadrupled for an interval of 100°; it is doubled at 1500° for the same temperature interval.

Then, except for some bodies exceptionally white, the emissive powers at high temperatures are superior to 0.5. By taking them equal to 0.75, the greatest error that will be made for the ordinary temperatures comprised between 1000° and 1500° will be from 25° to 50°.

Furthermore, in cases where the emissive power is unknown, an optical pyrometer will still give a consistent temperature scale for a given body, i.e., in terms of black-body temperatures (page 242).

We shall now describe the ordinary types of optical pyrometer and their calibration and then indicate some applications.

Optical Pyrometer of Le Chatelier. — Ed. Becquerel had proposed in 1864 to refer the measurement of high temperatures to the measurement of the intensity of red radiations emitted by incandescent bodies; but this method had never been realized in a complete manner, and still less employed. Le Chatelier, taking up the question, devised an experimental arrangement suitable for such measurements, and he determined an empirical *law of radiation* of substances in terms of the temperature.

Photometer. — For these measurements a photometric apparatus is required which gives, not as do the ordinary photometers, a measurement of the total illumination produced by a source (illumination which varies with the dimensions of this source), but the intrinsic brightness of each unit of surface. Use may be made of a photometer based on a principle due to Cornu.

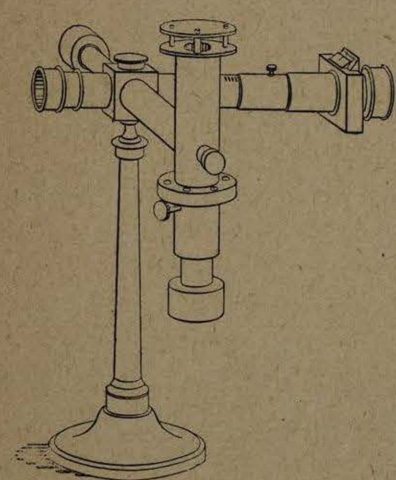

Fig. 108. Le Chatelier Pyrometer.

The apparatus (Figs. 108 and 109) consists essentially of a telescope which carries a small comparison lamp attached laterally. The image of the flame of this lamp is projected on a mirror M at 45° placed at the principal focus of the telescope. One adjusts for equality of intensity the images of the object that is viewed and of the comparison flame, these images being side by side.

The telescope comprises an objective in front of which is placed a cat's-eye diaphragm which admits of varying the effective aperture of this objective, and, beyond, a stand destined to carry tinted absorbing glasses.

At the focus of the objective is a mirror inclined at 45° which reflects the image of the lamp projected by an intermediary lens. An ocular, before which is placed in a set position a monochro-

matic glass, serves for observing the images of the flame and of the object.

To the lamp is fixed a rectangular diaphragm which stops the

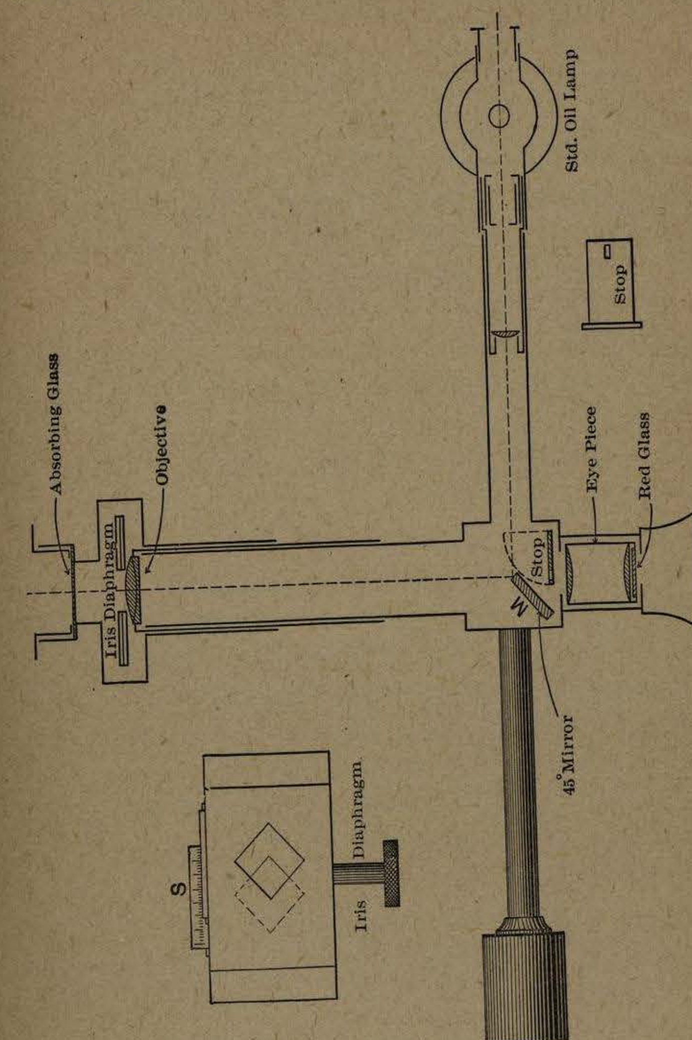

Fig. 109. Le Chatelier Pyrometer, Section.

luminous rays not utilized and which carries a stand to receive tinted absorbing glasses.

The edge of the mirror at 45° is in the plane of the image of the source studied, so that the reflected image and the direct image are side by side, separated only by the edge of the mirror. This mirror, according to a method devised by Cornu, is made of a plate of black glass cut with a diamond, which gives a very sharp edge.

In order to vary the relative intensities of the images, one thus employs simultaneously tinted glasses placed before one or the other of the two objectives, and the cat's-eye mentioned. A screw allows of varying the aperture of this cat's-eye, and a suitable scale S indicates the dimensions of this opening.

It is very important that the tinted glasses have an absorbing power as uniform as possible and do not possess absorption bands. These conditions are fulfilled by certain smoked glasses of ancient make (CuO,Fe_2O_3,MnO_2); for the fabrication of these glasses use is now made of the oxides of nickel and cobalt, which give absorption bands.

To determine the absorbing power of these glasses, a measurement is made with and without them; the ratio of the squares of the aperture of the cat's-eye gives the absorbing power.

For monochromatic screens one may use:

1. Red copper glass, which lets pass $\lambda = 659$,* about. The use of red glass is preferable to the others, as it is more nearly monochromatic and because measurements at low temperatures may be made with it, the first radiations emitted being red.

2. Green glass ($\lambda = 546$, about). The observations are then easier than in the red for some eyes, but they can be commenced only at higher temperatures.

3. Ammoniacal solution of copper oxide ($\lambda = 460$, about). The use of this last screen, which is far from monochromatic, is without interest; the eye is only slightly sensitive to the blue radiations, and these last become somewhat intense only at high temperatures. Blue glass (Schott and Genossen, No. F 3875) is preferable.

* Red glasses furnished by the maker Pellin, Paris, have an equivalent wave length of about $\lambda = 632$. Glasses which are more sharply monochromatic are furnished by Schott and Genossen of Jena, which firm also supplies very superior tinted absorption glasses; see page 335.

Adjustment of the Apparatus. — There are in the apparatus two parts which require very careful adjustment for best results, and these parts should consequently be so made as to admit of the necessary manipulation to obtain the desired effect.

1. The luminous beam coming from the lamp and which is reflected by the mirror, and that which comes directly from the object viewed, should penetrate into the eye in their totality. This condition is fulfilled if the images of the two objectives given by the ocular are superposed.

This is verified by examining with a lens these two images which are formed slightly behind the collar of the ocular. It is evidently necessary, in order to see them, to illumine the two objectives, one with the lamp, the other with any source of light. If the superposition does not exist, it is established by trial by turning the screws which hold the mirror. If it is not too severely jarred, the apparatus should remain indefinitely in adjustment.

2. In order that a steady light may be had, certain precautions in the adjustment of the comparison lamp are necessary. Le Chatelier recommends the employ of the same gasoline. The flame should have a constant height, equal, for example, to the window of the rectangular diaphragm placed before the flame. Its image should be cut exactly in two by the edge of the mirror, a result obtained by turning the lamp in its stand, which is eccentric (Fig. 110).

Finally, before taking an observation, it is necessary to wait some ten minutes for the lamp to come into heat equilibrium; then only does the flame possess a constant brightness.

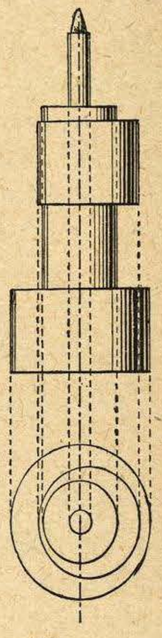

Fig. 110.
Mounting of Lamp.

Measurements. — In order to take an observation, a body selected as standard, as the flame of a stearine candle or the flame of a kerosene lamp, is examined; we observe: