The precision attainable with this form of instrument, over the range it may be controlled with the thermoelectric pyrometer, is shown from data obtained by Féry, assuming Stefan's law to hold in the form,

$$CE = d = 7.66\ T^4 \times 10^{-12},$$

where E is the total energy of radiation and d the galvanometer deflection and T the absolute temperature.

d.	Temperature from thermocouple.	Temperature from Stefan's law.	Δ in degrees.	Error in %.
11.0	844°	860°	+16°	1.85
14.0	914	925	+11	.84
17.7	990	990	0	.0
21.5	1054	1060	+ 6	.60
26.0	1120	1120	0	.0
32.2	1192	1190	− 2	.17
38.7	1260	1250	−10	.80
45.7	1328	1320	− 8	.60
52.5	1385	1380	− 5	.36
62.2	1458	1450	− 8	.50

It is evident, furthermore, that if the galvanometer has a uniformly graduated scale and the temperature T_1 corresponding to any one scale reading R_1 is known, that for any other reading R_2 may be found from the relation

$$T_2 = T_1 \sqrt[4]{\frac{R_2}{R_1}},$$

which also shows that errors in the galvanometer readings are divided by four when reduced to temperatures. For very high temperatures, deflections off the scale of the galvanometer will be obtained and the instrument will be excessively heated. Féry overcomes these difficulties by substituting a smaller diaphragm before the objective when the radiation is reduced in the ratio of the areas of the apertures.

The highest temperatures which may be estimated by this pyrometer are limited only by the applications of Stefan's law to this extreme region, and whether Stefan's law applies or not, consistent results, nevertheless, will be obtained.

Instead of the deflection galvanometer, it is better in work of precision to substitute a low-range potentiometer with sensitive galvanometer (see page 139).

The laboratory form of apparatus described above is not suitable for use in technical practice, and fluorite is difficult to get of sufficient size. An industrial pyrometer is readily made by substituting for the fluorite lens one of glass of wide aperture, and for the delicate galvanometer one of the same type and sensibility as used in thermoelectric work; the resulting instrument is robust and sufficiently sensitive for all practical uses, and as made has a range of from 800° to 1600° C., although the upper limit could readily be extended by having two scales on the instrument, provided with a diaphragm.

The indications of the industrial form of this pyrometer will not obey Stefan's law exactly, but the instrument may readily be calibrated by direct comparison either with a thermocouple or with a laboratory form of Féry instrument, and the scale of temperatures engraved on the instrument. Both types of instrument can be used to reach lower temperatures (650°) by means of more sensitive galvanometers.

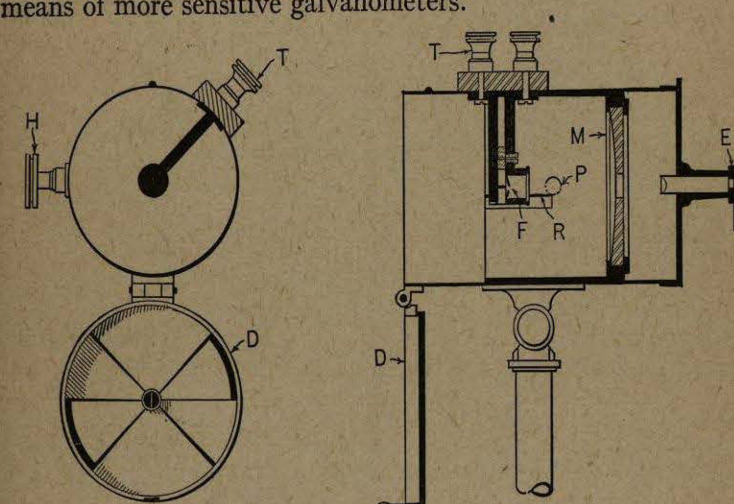

Fig. 100. Féry Mirror Telescope.

Féry Mirror Telescope. — This instrument (Fig. 100) was designed by Féry to replace both the laboratory and technical forms of lens telescope, and has been used very considerably in scientific and industrial work. As usually constructed the mirror is of gold on glass, and there is further provided an ingenious optical focusing device by means of which straight lines appear broken (Fig. 101), unless the instrument is in focus. The range

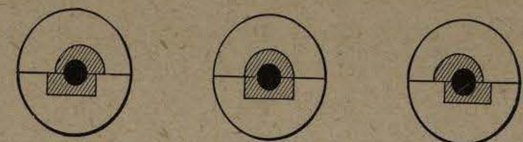

Fig. 101. Focusing Device.

of the instrument is increased by means of a sectored diaphragm, so that temperatures from the lowest to the highest may be read,

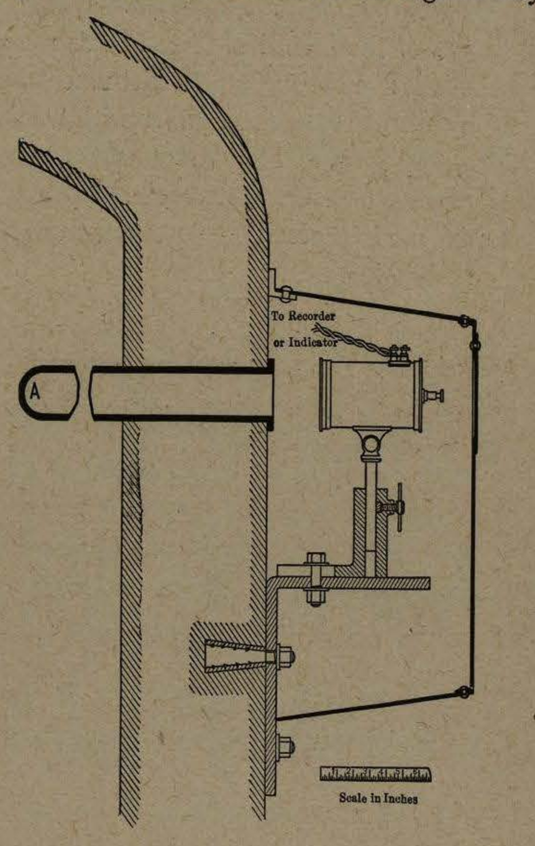

Fig. 102. Mounting on Kiln.

although for reading the lowest temperatures with any considerable precision a quite sensitive galvanometer is needed, or a more sensitive thermocouple may be used to produce the same effect.

The potentiometer method of reading for very accurate work may of course be substituted, as with the other forms of telescope. The robustness of the instrument has recently been increased for industrial work by substituting pivot galvanometers for the delicate suspended-coil instruments hitherto used. The gold mirror may be considerably tarnished without seriously influencing the readings; and if the aperture of the furnace sighted upon is of sufficient size and the telescope in focus, the tempera-

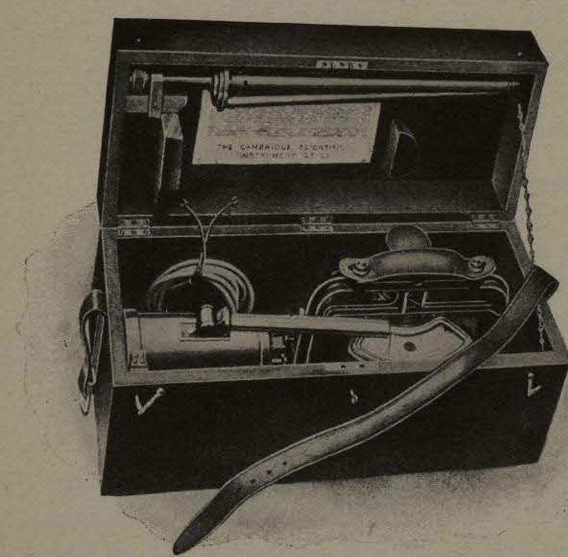

Fig. 103. Telescope and Galvanometer in Case.

ture readings are practically independent of the distance. The instrument takes its final reading very promptly with only slight creep. The readings of the instrument appear to be influenced somewhat by the area sighted upon and by the temperature of the region immediately outside the central cone of rays, or in other words, by stray radiation. For example, a Féry pyrometer, sighted into and clear through a resistance-tube furnace of 75 mm. aperture open its whole length with no diaphragm, will register several hundred degrees if the walls of the furnace are at 1100° C. An aperture of about 1-inch-wide opening per 1 yard of distance (2.5 cm. per 1 m.) is required for the usual industrial instruments. A suitable mounting for determining the temperatures of a kiln is shown in Fig. 102. A Féry pyrometer packed in its case with portable galvanometer mounted in gimbals is shown in Fig. 103.

Féry's Spiral Pyrometer. — Another method of registering the radiation focused by the telescope mirror has been devised by Féry, Fig. 104. The thermocouple and galvanometer are replaced by a bimetallic spring *S* placed at the mirror focus, carrying an aluminium pointer *P* which turns over a dial *D* graduated in degrees

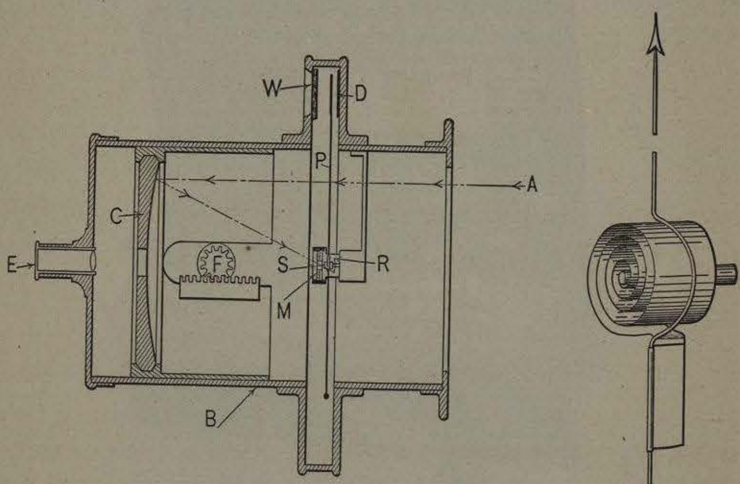

Fig. 104. Féry Spiral Pyrometer.

of temperature in response to the differential expansion of the spring when radiation is concentrated upon it. This instrument, therefore, has no accessories, and, in spite of a zero creep and set difficult to eliminate in the spring, this form of instrument may serve satisfactorily for many industrial uses where a moderate precision is desired.

Other Radiation Pyrometers (Thwing, Foster, Brown). — In Thwing's apparatus the reflecting mirror is replaced by a bright cone which by multiple reflection concentrates the radiation at its apex on one or more thermocouples in series with a portable galvanometer. This apparatus requires no focusing, but has to be sighted along the outside of the tube or adjusted in the direction until the reading of the galvanometer is a maximum

when the area sighted on is not large. Different sized apertures may be used at the open end to give different temperature ranges. Foster has also transformed the Féry telescope into a "fixed-focus pyrometer" (Fig. 105), by putting the thermocouple *D* and the aperture *EF* at the *conjugate foci* of the gold mirror *C*. A considerable area is required to sight upon. This instrument has to be pointed also by trial. In a similar instrument recently

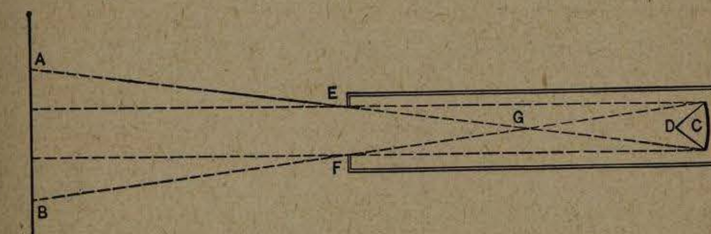

Fig. 105. Fixed-focus Pyrometer.

issued by the Brown Pyrometer Company, the sighting of the instrument is facilitated by the use of a finder such as used with photographic cameras.

The Féry pyrometer of constant-focus type has been coupled directly to a long closed-end tube by Whipple, thus rendering the instrument's readings independent of the nature of the furnace or material of which the temperature is sought, since the closed end tube is plunged directly into the hot region or melted metal to a sufficient depth, and the pyrometer proper is always focused on the bottom of this tube and indicates its temperature.

Mr. Whipple has used this instrument successfully for taking molten steel and brass temperatures in the crucible at temperatures for the former as high as 1550° C. The material of the extension tube will depend on the medium into which it is thrust.

All of the total-radiation pyrometers can be made self-registering by simply substituting for the indicating galvanometer a suitable recording instrument. The Féry mirror telescope is commonly used with the Cambridge thread recorder (Fig. 152).

Some Experimental Results. — To call attention to the scope of application of the radiation pyrometer, we may note some of the investigations carried out with one or another of its forms.

We have already cited the early attempt at an estimation of the sun's temperature by this method, and we shall return to this matter in the chapter on standardization, as well as to measurements on the temperature of the carbon arc with the Féry pyrometer.

Using his pyrometer, Thwing has measured the total emissivity (page 258, equation Ba) of streams of molten iron and copper. For cast iron in the liquid stream at 1300° to 1400° C., the intensity of radiation was found to be 0.29 that of the solid metal at the same temperature, and for mild steel at 1600° to 1650° C., the value was 0.28. These values appeared to hold to 1800° C. For copper Thwing finds the emissivity 0.14 that of a black body. Burgess, with a Féry mirror pyrometer, finds for copper $E_x = 0.15$, and for copper oxide $E_x = 0.60$, approximately. The observations of Burgess satisfy the following equations:

For liquid copper: $t = 3.55F - 1018$;
For cuprous oxide: $t = 1.41F - 169$;

when t is the true temperature centigrade, and F the reading of the Féry pyrometer calibrated in terms of the radiation from a black body. It will be seen that at 1083° C., the melting point of copper, the Féry instrument reads some 490° low when sighted on a clear surface of pure copper. A Féry pyrometer sighted on copper oxide at 700° C. will read higher than when sighted on an oxide-free surface of liquid copper at 1100° C. A similar interpretation of Thwing's results on iron shows that at 1520° C., for example, the melting point of pure iron, a radiation pyrometer sighted on the clear metal would read about 370° low, assuming $E_x = 0.29$ for pure iron. These illustrations are sufficient to show that, with a total-radiation pyrometer, true temperatures are given only under carefully specified conditions.

Conditions of Use. — It will be noticed that among the types of apparatus described in this chapter, there has been but one, the thermopile, in its several forms of thermoelectric telescope, which has as yet been used as a pyrometer. We have seen, however, that several of the other types of radiometric apparatus

may also readily be made to serve the purpose of temperature-measuring instruments, and that some of them may in certain cases offer theoretical and practical advantages over other forms of pyrometer.

In many industrial operations the temperatures are so high that no substance usable as an active part of a pyrometer, not even platinum, can resist for long their action or that of the chemical agents present. When it is desired, therefore, to have apparatus of continuous indications, or with which readings may be obtained without intervention of an observer, and at the same time unalterable by heat, it is necessary to resort to radiation pyrometers. That with them temperatures may be read off a robust form of portable millivoltmeter, and that such instruments are readily made self-registering, are also matters of great practical convenience.

It should be emphasized, however, that in general such pyrometers sighted upon objects in the open air will read too low in temperature, due to the selective radiating properties of all materials, although radiation pyrometers may be calibrated to give true surface temperatures sighted upon any substance whose radiating properties (page 259) are known; and in any case a self-consistent but arbitrary scale is obtained so long as the surface sighted upon does not change its emissivity. Fortunately, in many industrial operations, these limitations are easily overcome as well as others. Flames and furnace gases, which also affect seriously the readings of such pyrometers, may be avoided, together with the selective radiation errors, by sighting on the bottom of a closed-end tube inserted into the furnace. For example, a tube of fire clay or magnesia, or other material which will stand the temperature and chemical actions present, passing through the lining of the furnace, and penetrating into the midst of the latter for a distance of 0.5 to 1.0 meters, closed at the inner end and open at the outer, would give a radiating surface at the temperature of the furnace (Fig. 102), and would approach very closely to the ideal black-body conditions under which the radiation instruments will read correctly whatever be the nature of the object sighted upon at the bottom of such a tube. The radiation laws in their simplest form apply quite exactly to such a radiating tube, so that if the pyrometer has been calibrated by sighting it upon a black body, the calibration will hold for sighting into this tube, or when sighting through a small aperture into any clear, closed space at constant temperature. The closed-end tube above mentioned may evidently be used in hardening baths and in many other kinds of industrial installations.

Care has to be taken, in setting up and using any radiation pyrometer, that one allows sufficient area to sight upon. This is

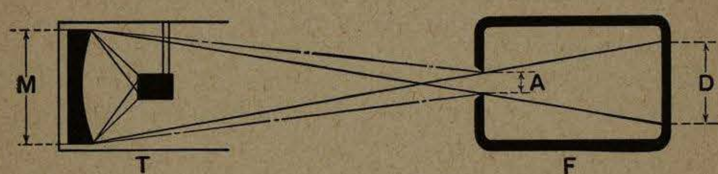

Fig. 106. Focusing on back of Furnace.

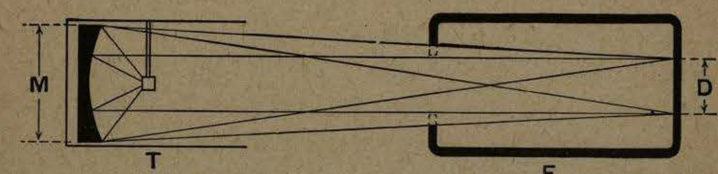

Fig. 107. Focusing on front of Furnace.

illustrated in Figs. 105, 106, and 107. The opening of the furnace *F* must be large enough so that the cone between *M* and *D* is not cut into if the instrument *T* is focused on *D*. A smaller opening is allowable if *T* is focused on some such plane as *A* (Fig. 106), when the furnace is at a uniform temperature.

Calibration. — It is a difficult matter to calibrate satisfactorily a total-radiation pyrometer to very high temperatures, and this is particularly true of most of the industrial types. Thus relatively large apertures are usually required, which necessitates correspondingly large furnaces, over whose visible area a constant temperature is to be maintained, and measured by some auxiliary calibrated instrument such as a thermoelectric, optical, or standard radiation instrument. With a large enough diaphragm to

sight upon at the center of a uniformly wound electric resistance furnace, unless great care is taken in the adjustments, there may exist, for example, differences of 30° to 50° C. between the two walls of a 2 mm. thick diaphragm as measured by thermocouples.

The total-radiation pyrometer is extremely sensitive, much more so than the optical instruments using a single color, to the lack of blackness, or to selective emission, in the source sighted upon; and this, combined with the large aperture requirement, complicates the problem. Furthermore, as the readings of these instruments are considerably influenced by the presence of flames, furnace gases, and dust, it is highly desirable to have a clear furnace to sight upon. While temperatures to 1400° or 1500° C. that are exactly measurable are obtainable in large electric resistance furnaces wound with platinum on porcelain, or in pots of metals with closed-end tubes inserted in the liquid or solid metal, no entirely satisfactory method of direct calibration free from the above sources of error to, say, 2000° or even 1700° C. appears to have been devised. Suitable iridium-tube furnaces lined with a glaze preventing evaporation of the iridium inwards could be constructed for use to 2000° C., but the cost of large enough furnaces of this type would be excessive and their life short. Carbon-tube furnaces lined with the available forms of magnesia or alumina are not satisfactory, due mainly to the porosity of the lining. This, perhaps, may be overcome by building such furnaces so as to prevent diffusion inwards by regulating the gas pressure from the center outwards. The presence of any kind of window before a total-radiation instrument, especially if it is to be used as a standard, is inadmissible, due to the unknown effect of the window absorption on the pyrometer readings. On the other hand, this type of pyrometer cannot be mounted in vacuo for calibration, as its readings would then differ from those obtained in air, due to different convection, radiation, and conduction conditions about the receiver.

From the fact that the usual forms of industrial instrument do not, in general, obey Stefan's law exactly, and often not even 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).