chapter fourteen

Thermometry and Pyrometry

REALIZATION OF TEMPERATURE SCALE

IN Chapter 8 we discussed the general idea of a temperature scale. To establish such a scale we need:

(i) some physical property of a substance—such as the volume of a particular liquid—which increases continuously with increasing hotness, but is constant at constant hotness;

(ii) two standard degrees of hotness—the fixed points (ice and steam)—which can be accurately reproduced.

The Fixed Points and Fundamental Interval

The temperature of melting ice and saturated steam are chosen as the fixed points on the Celsius temperature scale. We have seen that the atmospheric pressure must be specified in defining the steam point, but this is not necessary in defining the ice point, because the melting-point of ice changes very little with pressure (p. 296). On the other hand impurities in water do not affect the temperature of saturated steam, but impurities in ice do affect its melting-point (p. 221); the ice used in realizing the lower fixed point must therefore be prepared from pure water.

Then, if P is the chosen temperature-measuring quantity, its values P_0 at the ice point, and P_{100} at the steam point determine the fundamental interval of the scale: $P_{100}-P_0$. And the temperature θ_p on the P-scale, which corresponds to a value P_θ of P is, *by definition,*

$$\theta_P = \frac{P_\theta - P_0}{P_{100} - P_0} \times 100.$$

On the thermodynamic scale, the triple point of water (p. 319) is chosen as one fixed point and is defined as 273·16 K. The other fixed point is the absolute zero (see p. 190).

The Thermometric Substance and Property

Most thermometers are of the liquid-in-glass type, because it is simple and cheap; they contain either mercury or alcohol.

The mercury and alcohol scales agree fairly well with one another, and with either of the gas scales. The gas scales depend on the change of volume at constant pressure and of pressure at constant volume (p. 225). In practice the constant volume scale is always used, because a change of pressure is easier to measure accurately than a change of volume.

The mercury scale agrees better with the gas scales than does the alcohol scale. However, even the best mercury thermometers disagree slightly amongst themselves. The discrepancies may arise because the bores of the tubes are not uniform, or the mercury is impure, or the glass is not homogeneous.

In most accurate work, therefore, temperatures are measured by the changes in pressure of a gas at constant volume. At pressures of the order of one atmosphere, different gases give slightly different temperature scales, because none of them obeys the gas laws perfectly. But as the pressure is reduced, the gases approach closely to the ideal, and their temperature scales come together. By observing the departure of a gas from Boyle's law at moderate pressures it is possible to allow for its departure from the ideal; temperatures measured with the gas in a constant volume thermometer can then be converted to the values which would be given by the same thermometer if the gas were ideal.

The Constant-Volume Gas Thermometer

Fig. 14.1 shows a constant volume hydrogen thermometer, due to Chappius (1884). B is a bulb of platinum-iridium, holding the gas.

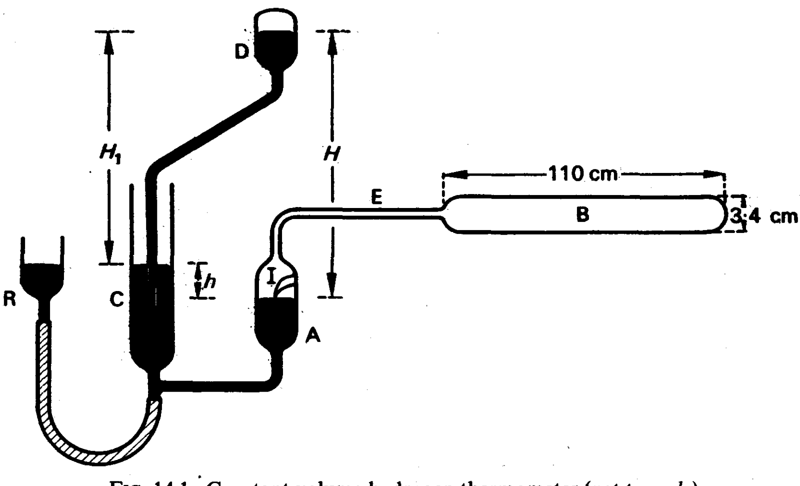

FIG. 14.1. Constant volume hydrogen thermometer (*not to scale*).

The volume is defined by the level of the index I in the glass tube A. The pressure is adjusted by raising or lowering the mercury reservoir R. A barometer CD is fitted directly into the pressure-measuring system; if H_1 is its height, and h the difference in level between the mercury surfaces in A and C, then the pressure H of the hydrogen, in mm mercury is

$$H = H_1 + h.$$

H is measured with a cathetometer.

The glass tubes A, C, D, all have the same diameter to prevent errors due to surface tension; and A and D are optically worked to prevent errors due to refraction (as in looking through common window-glass).

Observations made with a constant-volume gas thermometer must be corrected for the following errors:

(i) the expansion of the bulb B;
(ii) the temperature of the gas in the tube E and A, which lies between the temperature of B and the temperature of the room;
(iii) the temperature of the mercury in the barometer and manometer.

The expansion of the bulb can be estimated from its coefficient of cubical expansion, by using the temperature shown by the gas thermometer. Since the expansion appears only as a small correction to the observed temperature, the uncorrected value of the temperature may be used in estimating it. The tube E is called the 'dead-space' of the thermometer. Its diameter is made small, about 0·7 mm, so that it contains only a small fraction of the total mass of gas. Its volume is known, and the temperatures at various points in it are measured with mercury thermometers. The effect of the gas in it is then allowed for in a calculation similar to that used to calculate the pressure of a gas in two bulbs at different temperatures (p. 262). Mercury thermometers may be used to measure the temperatures because the error due to the dead-space is small; any error in allowing for it is of the second order of small quantities. For the same reason, mercury thermometers may be used to measure the temperature of the manometer and barometer.

A gas thermometer is a cumbersome instrument, demanding much skill and time, and useless for measuring changing temperatures. In practice, gas thermometers are used only for calibrating electrical thermometers—resistance thermometers and thermocouples. The readings of these, when they are used to measure unknown temperatures can then be converted into temperatures on the ideal gas scale.

The International Temperature Scale

Because of the wide use of electrical thermometers, a scale of temperature based on them is used throughout the laboratories of the world. It is called the *international scale of temperature*, and is defined so that temperatures expressed on it agree, within the limits of experimental accuracy, with the same temperatures expressed on the ideal gas scale.

For the purpose of calibrating electrical thermometers, subsidiary fixed points, in addition to the fundamental fixed points of ice and steam, have been determined with the constant-volume gas thermometer. They are all measured at an atmospheric pressure of 760 mm mercury. Their values are given, with those of the fundamental fixed points, in the following table.

FIXED POINTS OF THE INTERNATIONAL TEMPERATURE SCALE

(*a*) Boiling point of liquid oxygen	−182·970°C.
(*b*) Ice point (fundamental)	0·000°C.
(*c*) Steam point (fundamental)	100·000°C.
(*d*) Boiling-point of sulphur	444·600°C.
(*e*) Freezing-point of silver	960·800°C.
(*f*) Freezing-point of gold	1063·000°C.

The methods of interpolating between these fixed points will be described below.

Electric Thermometers

Electrical thermometers have great advantages over other types. They are more accurate than any except gas thermometers, and are quicker in action and less cumbersome than those.

The measuring element of a *thermo-electric thermometer* is the welded junction of two fine wires. It is very small in size, and can therefore measure the temperature almost at a point. It causes very little disturbance wherever it is placed, because the wires leading from it are so thin that the heat loss along them is usually negligible. It has a very small heat capacity, and can therefore follow a rapidly changing temperature. To measure such a temperature, however, the e.m.f. of the junction must be measured with a galvanometer, instead of a potentiometer, and some accuracy is then lost.

The measuring element of a *resistance thermometer* is a spiral of fine-wire. It has a greater size and heat capacity than a thermojunction, and cannot therefore measure a local or rapidly changing temperature. But, over the range from about room temperature to a few hundred degrees Centigrade, it is more accurate.

Resistance Thermometers

Resistance thermometers are usually made of platinum. The wire is wound on two strips of mica, arranged crosswise as shown in Fig.

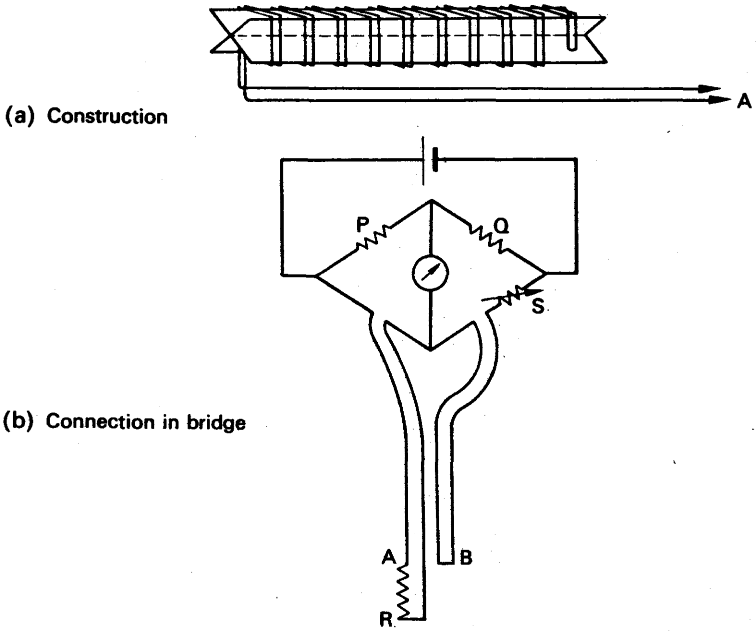

FIG. 14.2. Platinum resistance thermometer ($P = Q$, so that B compensates A; and $S = R$).

14.2 (*a*). The ends of the coil are attached to a pair of leads A, for connecting them to a Wheatstone bridge. A similar pair of leads B is near to the leads from the coil, and connected in the adjacent arm of the bridge (Fig. 14.2 (*b*)). At the end near the coil, the pair of leads B is short-circuited. If the two pairs of leads are identical, their resistances are equal, whatever their temperature. Thus if $P = Q$ the dummy pair, B, just compensates for the pair A going to the coil; and the bridge measures the resistance of the coil alone.

The platinum resistance thermometer is used to measure temperatures on the international scale between the boiling-point of oxygen and 630°C (630°C is approximately the freezing-point of antimony, but it is not a fixed point on the scale). The platinum used in the coil must be of high purity. Its purity is judged by the increase in its resistance from the ice point to the steam point. Thus if R_0 and R_{100} are the resistances of the coil at these points, then the coil is fit to reproduce the international temperature scale if

$$\frac{R_{100}}{R_0} > 1{\cdot}3910.$$

From the boiling-point of oxygen (−182·970°C) to the ice-point, the temperature θ, on the international scale, is given by the equation

$$R_\theta = R_0[1+A\theta+B\theta^2+C(\theta-100)\theta^3] \quad . \quad . \quad (1)$$

Here R_θ is the resistance of the coil, and A, B, C are constants. The constants A and B are determined in a way which we shall describe shortly. When they are known the constant C can be determined from the value of R_θ at the boiling-point of oxygen.

From the ice-point to 630°C the temperature θ is given by

$$R_\theta = R_0(1+A\theta+B\theta^2).$$

The constants A and B are the same as A and B in equation (1); they can be determined by measuring R_θ at the steam point and the sulphur point (444·600°C).

At temperatures below the boiling-point of oxygen the resistance of platinum changes rather slowly with temperature. The resistance of lead changes more rapidly, and resistance thermometers of lead wire have been used.

Thermocouples

Between 630°C and the gold point (1063·0°C) the international temperature scale is expressed in terms of the electromotive force of a thermocouple. The wires of the thermocouple are platinum, and platinum-rhodium alloy (90 per cent Pt.: 10 per cent Rh.). Since the e.m.f. is to be measured on a potentiometer, care must be taken that thermal e.m.f.'s are not set up at the junctions of the thermocouple wires and the copper leads to the potentiometer. To do this three junctions are made, as shown in Fig. 14.3 (*a*). The junctions of the copper leads to the thermocouple wires are both placed in melting ice. The electromotive force of the whole system is then equal to the e.m.f. of two platinum/platinum-rhodium junctions, one in ice and the other at the unknown temperature (Fig. 14.3 (*b*)).

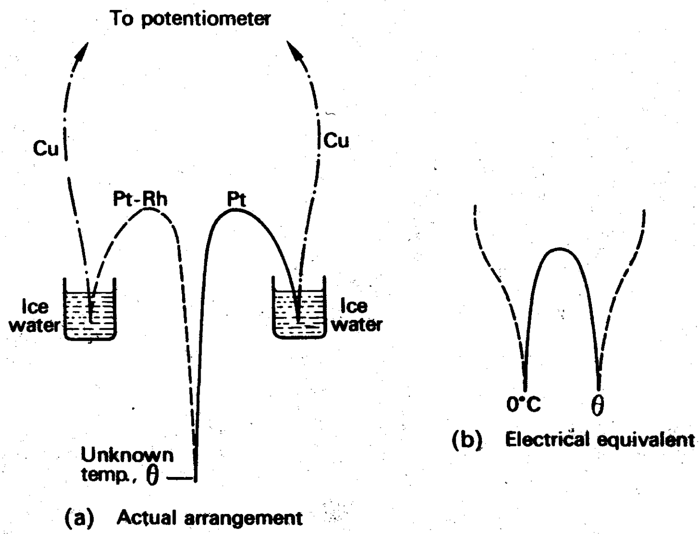

FIG. 14.3. Use of thermocouples.

The international temperature θ corresponding to an e.m.f. E is given by

$$E = a + b\theta + c\theta^2,$$

where a, b and c are constants. The values of the constants are determined by measurements at the gold point (1063·0°C), the silver point (960·8°C), and the temperature of freezing antimony (about 630·3°C). Since the freezing-point of antimony is not a fixed point on the international scale, its value in a given experiment is directly measured with a resistance thermometer. This temperature therefore serves to link the resistance and thermo-electric regions of the temperature scale.

Other Thermocouples

Because of their convenience, thermocouples are used to measure temperatures outside their range on the international scale, when the highest accuracy is not required. The arrangement of three junctions and potentiometer may be used, but for less accurate work the potentiometer may be replaced by a galvanometer G, in the simpler arrangement of Fig. 14.4 (*a*). The galvanometer scale may be calibrated to read directly in temperatures, the known melting-points of metals like tin and lead being used as subsidiary fixed points. For rough work, particularly at high temperatures, the cold junction may be omitted (Fig. 14.4 (*b*)). An uncertainty of a few degrees in a thousand is often of no importance.

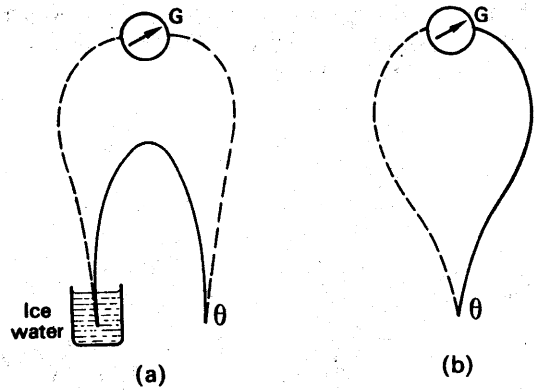

FIG. 14.4. Simple thermojunction thermometer.

E.M.F.'S OF THERMOJUNCTIONS
(In millivolts, cold junction at 0°C)

Temp. of hot junction °C	Pt./Pt.–10% Rh.	Chromel[1]/ Alumel[2]	Copper/ Constantan[3]	Iron/ Constantan
100	0·64	4·1	4	5
200	1·44	8·1	9	11
300	2·32	12·2	15	16
400	3·25	16·4	21 [5]	22
500	4·22	20·6		27
600	5·22	24·9		33
700	6·26	29·1		39
800	7·33	33·3		45
900	8·43	37·4		
1000	9·57	41·3		
1200	11·92 [4]	48·8		
1400	14·31	55·8		
1600	16·67			

1. Cr-Ni alloy.
2. Al-Ni alloy.
3. 60 per cent Cu, 40 per cent Ni (sometimes called Eureka).
4. Liable to a change of fundamental interval if heated above 1,100°C.
5. Cu starts to oxidize.

Intermediate Metals

Fig. 14.5 (*a*) shows two metals of a thermocouple, A, B, separated by a third metal, C. The metal C may be, for example, a film of the solder used to join A and B. At a given temperature θ, the e.m.f. E of the couple ACB is found, by measurement, to be equal to that of a simple couple AB, formed by twisting or welding the the wires together (Fig. 14.5 (*b*)). This is true provided that the junctions of A to C, and C to B, are both at the temperature θ. An intermediate metal, at a uniform temperature, does not therefore affect the e.m.f. of a thermojunction.

Expanding-liquid Thermometers: Mercury-in-glass

Mercury freezes at -39°C and boils, under atmospheric pressure, at 357°C. Mercury thermometers can be made to read up to about 550°C,

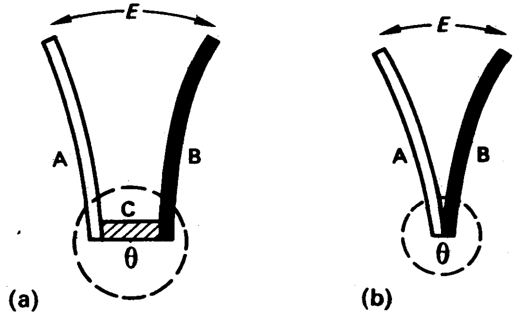

FIG. 14.5. Intermediate metal in a thermojunction.

however, by filling the space above the liquid with nitrogen, which is compressed as the mercury expands, and raises its boiling-point.

A mercury thermometer has a much greater heat capacity than a thermocouple, and cannot follow a rapidly changing temperature. Also glass, when it has been warmed and then cooled, does not immediately contract back to its original volume at the lower temperature. If a low temperature is measured immediately after a high one, the value given by a mercury thermometer tends to be too low. With modern hard glass (Jena glass) this effect is small; but with a cheap thermometer the ice point may be as much as half a degree low if taken immediately after the steam point has been checked.

A mercury thermometer is filled by warming and dipping, as a weight thermometer (p. 283). The mercury in its bulb is then boiled, to drive out air. It is then allowed to cool and draw in the requisite amount of mercury. Finally it is warmed a little above the highest temperature it is to measure, sealed off, and left for about a year—to age. During the ageing period the glass slowly contracts after its strong heating, and at the end of the period the thermometer is calibrated.

Clinical Thermometers

A clinical thermometer has a fine stem, divided into fifths or tenths of a degree, and calibrated over only a small range: 95°–110°F or 35°–45°C (Fig. 14.6). The stem is thickened on the side remote from the gradua-

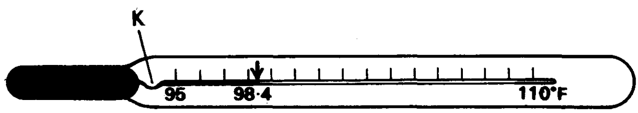

FIG. 14.6. Clinical thermometer.

tions so that it acts as a lens, to magnify the fine mercury thread. At room temperature the mercury retreats right into the bulb. Between the bulb and the graduations is a fine kink K. When the bulb is warmed the mercury is forced through the kink into the stem. But when the bulb is cooled, the mercury does not flow back past the kink—it stays in the stem, so that the temperature can be read at leisure. It is then shaken back into the bulb.

Mercury-in-steel Thermometers

For industrial purposes mercury-in-steel thermometers are used. They consist of a steel bulb B, connected by a long steel capillary S to a coiled steel tube C (Fig. 14.7). The whole is filled with mercury, and when

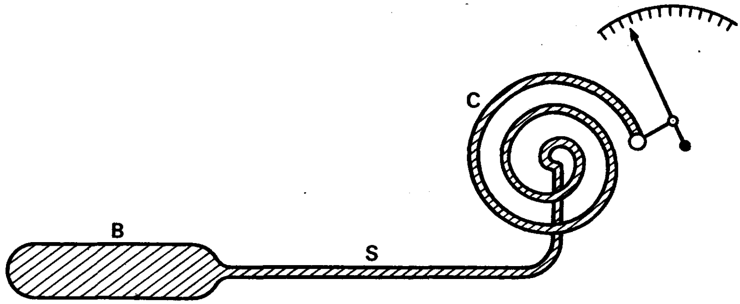

FIG. 14.7. Mercury-in-steel thermometer (*diagrammatic*).

the bulb is warmed the expansion of the mercury makes the coil unwind. The unwinding of the coil actuates a pointer, and indicates the temperature of the bulb. The distance between the bulb and the indicating dial may be many feet.

Alcohol Thermometers

Ethyl alcohol boils at 78°C, and freezes at −115°C. Alcohol thermometers are therefore used in polar regions. Alcohol is also used in some of the maximum and minimum thermometers which we are about to describe.

Maximum and Minimum Thermometers

Meteorologists observe the highest and lowest temperatures reached by the air day and night. They use a *maximum thermometer* which is a mercury thermometer containing a small glass index I (Fig. 14.8 (*a*)). The thermometer is laid horizontally, in a louvred screen. When the temperature rises the mercury pushes the index along, but when the temperature falls the mercury leaves the index behind. The maximum temperature is therefore shown by the end of the index nearer the mercury. After each observation, the index is brought back to the mercury by tilting the thermometer.

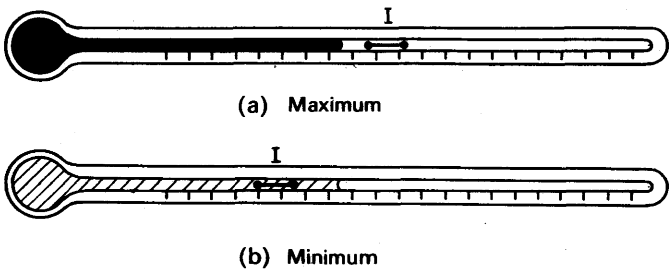

FIG. 14.8. Meteorological thermometers.

A *minimum thermometer* is similar to a maximum, except that it contains alcohol instead of mercury. When the alcohol expands it flows past the index, but when it contracts it drags the index back, because of its surface tension (Fig. 14.8 (*b*)). The end of the index nearer the meniscus therefore shows the minimum temperature. The index is re-set by tilting.

A combined *maximum and minimum thermometer* was invented by Six in 1782. Its construction is shown in Fig. 14.9. The bulb A, and the part B of the stem, contain alcohol; so does the part D of the stem, and the lower part of the bulb E. The part C of the stem contains mercury, and the upper part of the bulb E contains air and saturated alcohol vapour. The indices G and H are made of iron, and are fitted with springs pressing against the walls of the stem. When the temperature rises, the expansion of the large volume of alcohol in A forces the mercury round, and compresses the gases in E. The mercury pushes the index G up the tube. When the temperature falls, the alcohol in A contracts, and the mercury retreats. But the spring holds the index G, and the alcohol flows past it. Thus the bottom of G shows the maximum temperature. Similarly, the bottom of H shows the minimum. The indices are re-set by dragging them along from the outside with a magnet.

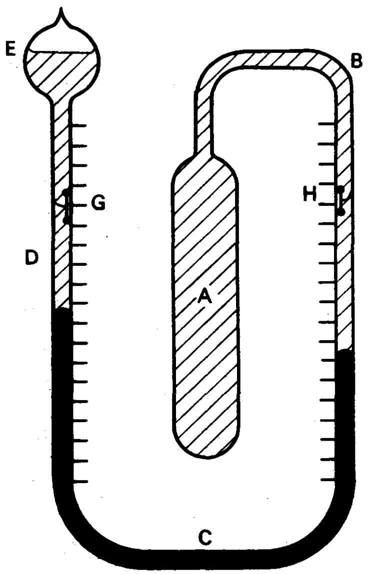

FIG. 14.9. Combined maximum and minimum thermometer.

Bimetal Strip Thermometers

If a bimetal strip is wound into a spiral, with the more expansible metal on the inside, then the spiral will uncoil as the temperature rises. The movement of the spiral can be made to turn a pointer, and to act as a thermometer. Instruments of this kind do not hold their calibration as well as liquid-in-glass thermometers.

PYROMETERS

High temperatures are usually measured by observing the radiation from the hot body, and the name *Pyrometry* is given to this measurement. Before describing pyrometers, however, we may mention some other, rough, methods which are sometimes used. One method is to insert in the furnace a number of ceramic cones, of slightly different compositions; their melting-points increase from one to the next by about 20°C. The temperature of the furnace lies between the melting-points of adjacent cones, one of which softens and collapses, and the other of which does not.

The temperature of steel, when it is below red heat, can be judged by its colour, which depends on the thickness of the oxide film upon it. Temperatures below red heat can also be estimated by the use of paints, which change colour at known temperatures.

Radiation pyrometers can be used only above red-heat (about 600°C). They fall into two classes:

(i) *total radiation pyrometers*, which respond to the total radiation from the hot body, heat and light;
(ii) *optical pyrometers*, which respond only to the visible light.

Optical Pyrometers

Fig. 14.10 illustrates the principle of the commonest type of optical pyrometer, called a *disappearing filament pyrometer*. It consists essen-

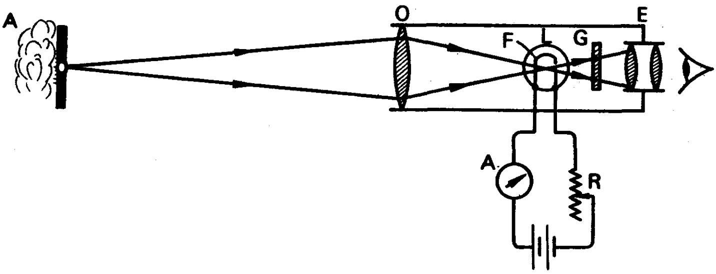

FIG. 14.10. Optical radiation pyrometer (*not to scale*).

tially of a low power telescope, OE, and a tungsten filament lamp L. The eyepiece E is focused upon the filament F. The hot body A whose temperature is to be found is then focused by the lens O so that its image lies in the plane of F. The light from both the filament and the hot body passes through a filter of red glass G before reaching the eye. If the body is brighter than the filament, the filament appears dark on a bright ground. If the filament is brighter than the body, it appears bright on a dark ground. The temperature of the filament is adjusted, by adjusting the current through it, until it merges as nearly as possible into its background. It is then as bright as the body. The rheostat R which adjusts the current is mounted on the body of the pyrometer, and so is the ammeter A which measures the current. The ammeter is calibrated directly in degrees Centigrade or Fahrenheit. A pyrometer of this type can be adjusted to within about 5°C at 1000°C; more elaborate types can be adjusted more closely.

The range of an optical pyrometer can be extended by introducing a filter of green glass between the objective O and the lamp L; this reduces the brightness of the red light. A second scale on the ammeter is provided for use when the filter is inserted.

The scale of a radiation pyrometer is calibrated by assuming that the radiation is black-body radiation (p. 352). If—as usual—the hot body is not black, then it will be radiating less intensely than a black body at the same temperature. Conversely, a black body which radiates with the same intensity as the actual body will be cooler than the actual body. Thus the temperature indicated by the pyrometer will be lower than the true temperature of the actual, not black, body. A correction must be applied to the pyrometer reading, which depends on the spectral emissivity of the body for red light. The wavelength λ for which the spectral emissivity e_λ must be known is the average wavelength of light transmitted by the red filter—usually about 6500 A.U.

The following tables give e_λ for various substances, and the corrections to be added for various values of e_λ.

SPECTRAL EMISSIVITIES, e_λ
(At 650 nm)

Substance	Solid	Liquid	Substance	Solid	Liquid
Carbon	0·85	—	Nickel	0·35	—
Copper	0·1	0·15	Nickel oxidized	0·9	—
Copper oxidized	0·7	—	Platinum	0·35	0·35
Gold	0·15	0·2	Silver	0·1	—
Iron	0·35	0·35	Slag	—	0·65
Iron oxidized	0·95	—	Tungsten	0·45	—
Nichrome	0·9	—			

OPTICAL PYROMETER CORRECTIONS
(λ = 650 nm)

[*To be added to observed temperature*]

Observed temp., °C	0·3	0·4	0·5	0·6	0·7	0·8	0·9
600	44	34	26	18	13	8	4
800	67	50	37	27	19	12	6
1000	95	71	53	39	27	17	8
1200	129	96	71	52	36	22	10
1400	169	125	93	67	46	28	13
1600	214	159	117	85	58	35	17
1800	265	196	145	105	72	44	20
2000	322	238	176	127	87	53	25
2500	495	362	266	190	131	78	38
3000	713	516	377	269	183	110	53

Total Radiation Pyrometers

Total radiation pyrometers are less common than optical pyrometers. As we shall see, they can only be used when the source of radiation is of considerable size—such as the open door of a furnace—whereas an optical pyrometer can be used on a very small body such as a lamp-filament.

Fig. 14.11 illustrates the principle of a Féry total radiation pyrometer. The blackened tube A is open at the end B; at the other end C it carries an eye-piece E. D is a thermocouple attached to a small blackened

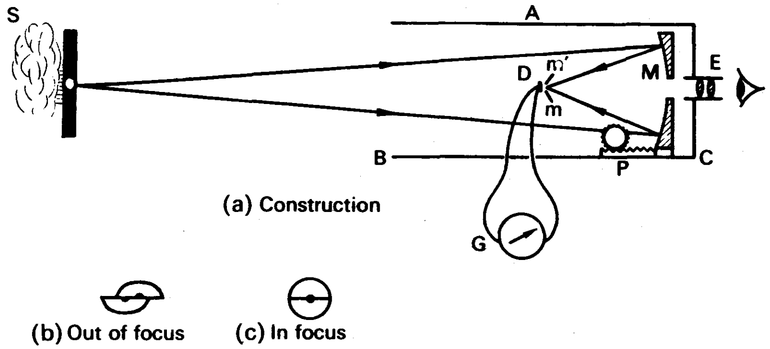

FIG. 14.11. Féry total radiation pyrometer.

disc of copper, which faces the end C of the tube and is shielded from direct radiation. M is a gold-plated mirror, pierced at the centre to allow light to reach the eye-piece, and moveable by a rack and pinion P.

In use, the eyepiece is first focused upon the disc D. The mirror M is then adjusted until the furnace is also focused upon D. Since a body which is black or nearly so shows no detail, focusing it upon D by simply looking at the image would be almost impossible. To make the focusing easier, two small plane mirrors m′, m are fitted in front of D. They are inclined with their normals at about 5° to the axis of the tube, and are pierced with semi-circular holes to allow radiation from M to reach the disc. The diameter of the resulting circular hole is less than that of the disc. When the source of heat is not focused on the disc, the two mirrors appear as at (*b*) in the figure; when the focusing is correct, they appear as at (*c*). The source must be of such a size that its image completely fills the hole.

The radiation from the source warms the junction and sets up an electromotive force. A galvanometer G connected to the junction is then deflected, and can be calibrated to read directly the temperature of the source.

The calibration gives the correct temperature if the source is a black body. If the source is not black, its total radiation is equal to that of a black body at some lower temperature; the pyrometer therefore reads too low. If the total emissivity of the source is known, a correction can be made for it. This correction is greater than it would be if an optical pyrometer were used, that is to say, departure from perfect blackness causes less error in an optical pyrometer than in a total radiation one.

The Foster Pyrometer

Another type of total radiation pyrometer is the Foster fixed-focus instrument (Fig. 14.12); it also uses a thermojunction with blackened disc. A is an open diaphragm, so placed that it and the thermojunction D are at conjugate foci of the mirror M. The thermojunction then collects all the radiation entering through A but, since it is much smaller than A, it is raised to a higher temperature than if its disc were the size of A. The radiation entering through A is limited to that within

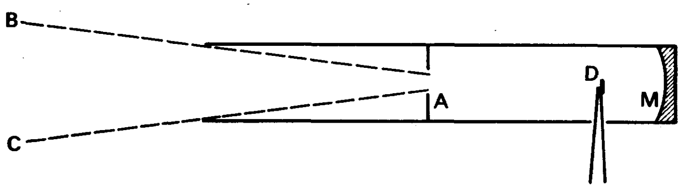

FIG. 14.12. Fixed focus total radiation pyrometer.

the cone ABC; as long as the whole of this cone is intersected by the hot source, the amount of radiation reaching the thermocouple is independent of the distance to the source (compare the use of a cone with a thermopile, p. 350).

Comparison of Pyrometers: the International Scale

Total radiation and optical pyrometers agree within the limits of experimental error—$\frac{1}{2}°$ at 1750°C, about 4° at 2800°C. The choice between them is decided solely by convenience. The international temperature scale above the gold-point (1063·0°C) is defined in terms of an optical pyrometer.

Extension of Range by Sectored Disc

The range of a radiation pyrometer can be extended by cutting down the radiation admitted to it. A disc from which an angle θ radians has been cut out is rotated in front of the pyrometer, as shown in Fig. 14.13, so that the radiation entering is cut down in the ratio $\theta/2\pi$. The pyrometer then indicates a temperature T_1, which is less than the true temperature T_2 of the source. The temperatures T are expressed in K to simplify the calculation which follows.

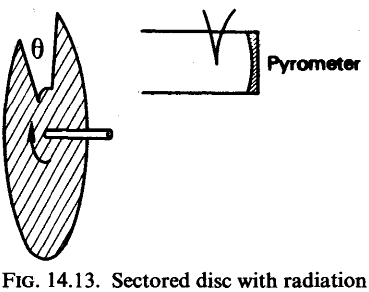

FIG. 14.13. Sectored disc with radiation pyrometer.

If the pyrometer is of the total radiation type, then we can use Stefan's law. The radiation from a body at T_2 K is proportional to T_2^4. The pyrometer receives radiation represented by the temperature T_1, and therefore proportional to $T_1{}^4$.

Therefore $$\frac{\theta}{2\pi} = \frac{T_1{}^4}{T_2{}^4},$$

whence $$T_2 = T_1\left(\frac{2\pi}{\theta}\right)^{\frac{1}{4}}.$$

In this way the surface temperature of the sun has been estimated. The value found agrees with that estimated from the wavelength of the sun's most intense radiation (p. 353); it is about 6000 K.

A sectored disc can be used to extend the range of an optical pyrometer, but the calculation is more difficult than for a total radiation pyrometer.

EXAMPLES

1. How is Celsius temperature defined (*a*) on the scale of a constant-pressure gas thermometer, (*b*) on the scale of a platinum resistance thermometer? A constant mass of gas maintained at constant pressure has a volume of 200·0 cm^3 at the temperature of melting ice, 273·2 cm^3 at the temperature of water boiling under standard pressure, and 525·1 cm^3 at the normal boiling-point of sulphur. A platinum wire has resistances of 2·000, 2·778 and 5·280 ohms at the same temperatures. Calculate the values of the boiling-point of sulphur given by the two sets of observations, and comment on the results. (*N.*)

First part (*a*). The temperature θ on the gas thermometer scale is given by

$$\theta = \frac{V_\theta - V_0}{V_{100} - V_0} \times 100,$$

where V_θ, V_0, V_{100} are the respective volumes of the gas at constant pressure at the temperature concerned, the temperature of melting ice, and the temperature of steam at 76 cm mercury pressure. (*b*) The temperature θ_p on the platinum resistance thermometer scale is given by

$$\theta_p = \frac{R_\theta - R_0}{R_{100} - R_0} \times 100,$$

where R_θ, R_0, R_{100} are the respective resistances of the platinum at the temperature concerned, the temperature of melting ice, and the temperature of steam at 76 cm mercury.

Second part. On the gas thermometer scale, the boiling-point of sulphur is given by

$$\theta = \frac{525{\cdot}1 - 200{\cdot}0}{273{\cdot}2 - 200{\cdot}0} \times 100$$

$$= 444{\cdot}1\text{°C}.$$

On the platinum resistance thermometer scale, the boiling-point is given by

$$\theta_p = \frac{5{\cdot}280 - 2{\cdot}000}{2{\cdot}778 - 2{\cdot}000} \times 100$$

$$= 421{\cdot}6\text{°C}.$$

The temperatures recorded on the thermometers are therefore different. This is due to the fact that the variation of gas pressure with temperature at constant volume is different from the variation of the electrical resistance of platinum with temperature.

2. Explain how a Celsius temperature scale is defined, illustrating your answer by reference to a platinum resistance thermometer.

The resistance R_t of a platinum wire at temperature t°C, measured on the gas scale, is given by $R_t = R_0(1 + at + bt^2)$, where $a = 3{\cdot}800 \times 10^{-3}$ and $b = -5{\cdot}6 \times 10^{-7}$. What temperature will the platinum thermometer indicate when the temperature on the gas scale is 200°C? (*O. & C.*)

First part. The temperature θ_p in °C on a resistance thermometer scale is given by the relation

$$\theta_p = \frac{R_\theta - R_0}{R_{100} - R_0} \times 100,$$

where R_θ, R_0, R_{100} are the respective resistances at the temperature concerned, at 0°C, and at 100°C.

Second part. $R_t = R_0(1+at+bt^2)$

$$\therefore R_{200} = R_0(1+200a+200^2b)$$

and $R_{100} = (R_0(1+100a+100^2b)$.

$$\therefore \theta_p = \frac{R_{200}-R_0}{R_{100}-R_0}\times 100$$

$$= \frac{R_0(1+200a+200^2b)-R_0}{R_0(1+100a+100^2b)-R_0}\times 100$$

$$= \frac{200a+200^2b}{a+100b} = \frac{200(a+200b)}{a+100b}$$

$$= 200\frac{(3{\cdot}8\times 10^{-3}-11{\cdot}2\times 10^{-5})}{3{\cdot}8\times 10^{-3}-5{\cdot}6\times 10^{-5}}$$

$$= \frac{200\times 0{\cdot}003688}{0{\cdot}003744} = 197°\text{C}.$$

EXERCISES 14

1. How is a scale of temperature defined? What is meant by a temperature of 15°C?

On what evidence do you accept the statement that there is an absolute zero of temperature at about −273°C?

In a special type of thermometer a fixed mass of gas has a volume of 100·0 cm^3 and a pressure of 81·6 cm of mercury at the ice point, and volume 124·0 units, with pressure 90·0 units at the steam point. What is the temperature when its volume is 120·0 units and pressure 85·0 units, and what value does the scale of this thermometer give for absolute zero? Explain the principle of your calculation. (*O. & C.*)

2. Describe the structure of (*a*) a platinum resistance thermometer, (*b*) an optical pyrometer. Explain, giving details of the auxiliary electrical circuits required, how you would use each type of thermometer to measure a temperature, assuming that the instrument has already been calibrated over the required range. (*L.*)

3. Explain what is meant by a change in temperature of 1 deg C on the scale of a platinum resistance thermometer.

Draw and label a diagram of a platinum resistance thermometer together with a circuit in which it is used.

Give *two* advantages of this thermometer and explain why, in its normal form, it is unsuited for measurement of varying temperatures.

The resistance R_t of platinum varies with the temperature t°C as measured by a constant volume gas thermometer according to the equation

$$R_t = R_0(1+8{,}000\alpha t-\alpha t^2)$$

where α is a constant. Calculate the temperature on the platinum scale corresponding to 400°C on this gas scale. (*N.*)

4. Give the essential steps involved in setting up a scale of temperature. Explain why scales based on different properties do not necessarily agree at all temperatures. At what temperature or temperatures do these different scales agree?

The volume of some air at constant pressure, and also the length of an iron rod, are measured at 0°C and again at 100°C with the following results:

	0°C	100°C
Volume of air (cm^3)	28·5	38·9
Length of rod (cm)	100·00	100·20

Calculate (*a*) the absolute zero of this air thermometer scale, and (*b*) the length of the iron rod at this temperature if its expansion is uniform according to the air scale. (*C.*)

5. Describe the structure of a constant volume gas thermometer. Describe also the method of calibrating it and using it to determine the boiling point of a salt solution.

Compare this thermometer as a means of measuring temperature with (*a*) a mercury-in-glass thermometer, (*b*) a thermoelectric thermometer. (*L.*)

6. State what is meant by a temperature on the centigrade (Celsius) scale of a platinum resistance thermometer.

Point out the relative merits of (*a*) a platinum resistance thermometer, and (*b*) a thermoelectric thermometer for measuring (i) the rise in temperature of the water flowing through a continuous flow calorimeter, and (ii) the temperature of a small crystal as it is being heated rapidly. (*N.*)

7. Three types of thermometer in common use are based on (*a*) the expansion of a fluid, (*b*) the production of an electromotive force, (*c*) the variation of electrical resistance. Describe briefly one example of each and the way in which it is used. In each case, state how a value of the temperature on a centigrade scale is deduced from the quantities actually measured.

If all three of the thermometers you have described were used to measure the temperature of the same object, would they give the same result? Give reasons for your answer. (*O. & C.*)

8. Explain the principle underlying the establishment of a centigrade temperature scale in terms of some suitable physical property.

What type of thermometer would you choose for use in experiments involving (*a*) the plotting of a cooling curve for naphthalene in the region of its melting point, (*b*) finding the boiling point of oxygen, (*c*) the measurement of the thermal conductivity of a small crystal? In each instance give reasons for your choice.

If the resistance R_t of the element of a resistance thermometer at a temperature of t°C on the ideal gas scale is given by $R_t = R_0(1+At+Bt^2)$, where R_0 is the resistance at 0°C and A and B are constants such that $A = -6{\cdot}50\times10^3 B$, what will be the temperature on the scale of the resistance thermometer when t = 50·0°C? (*L.*)

9. Explain briefly what is meant by a temperature of θ°C on (*a*) the mercury-in-glass scale, (*b*) the constant-pressure hydrogen scale, (*c*) the platinum resistance scale.

For what range of temperatures could (i) a platinum resistance thermometer, (ii) an optical pyrometer be employed? Describe the structure and the method of use of *one* of these instruments. (*L.*)

10. Explain the principle of a constant volume gas thermometer and describe a simple instrument suitable for measurements in the range 0° to 100°C. What factors determine (*a*) the sensitivity and (*b*) the accuracy of the instrument you describe?

A certain gas thermometer has a bulb of volume 50 cm^3 connected by a capillary tube of negligible volume to a pressure gauge of volume 5·0 cm^3. When the bulb is immersed in a mixture of ice and water at 0°C, with the pressure gauge at room temperature (17°C), the gas pressure is 700 mm Hg. What will be the pressure when the bulb is raised to a temperature of 50°C if the gauge is maintained at room temperature? You may assume that the gas is ideal and that the expansion of the bulb can be neglected.

11. Give a brief account of the principles underlying the establishment of a scale of temperature and explain precisely what is meant by the statements that the temperature of a certain body is (*a*) t°C on the constant volume air scale, (*b*) t_P°C on the platinum resistance scale, and (*c*) t_T°C on the Cu-Fe thermocouple scale. Why are these three temperatures usually different?

Describe an optical pyrometer and explain how it is used to measure the temperature of a furnace. (*N.*)

12. What is the general method of calibrating any type of thermometer? Describe *briefly* the method of using *three* of the following temperature measuring devices, and give the temperature range in which they are most usefully employed: (i) platinum resistance thermometer, (ii) mercury-in-glass thermometer, (iii) helium gas thermometer, (iv) optical pyrometer. (*L.*)

13. Explain the precautions taken in verifying the position of the fixed points on the stem of a mercury-in-glass thermometer.

Describe a constant volume air thermometer. How could such a thermometer be used to determine the melting-point of a solid such as naphthalene? What advantage has the gas thermometer and for what purpose is it used? (*L.*)

14. Tabulate various physical properties used for measuring temperature. Indicate the temperature range for which each is suitable.

Discuss the fact that the numerical value of a temperature expressed on the scale of the platinum resistance thermometer is not the same as its value on the gas scale except at the fixed points.

If the resistance of a platinum thermometer is 1·500 ohms at 0°C, 2·060 ohms at 100°C and 1·788 ohms at 50°C on the gas scale, what is the difference between the numerical values of the latter temperature on the two scales? (*N.*)

15. Explain how a centigrade temperature scale is defined, illustrating your answer by reference to a platinum resistance thermometer.

The resistance R_t of a platinum wire at temperature t°C, measured on the gas scale, is given by $R_t = R_0(1 + at + bt^2)$, where $a = 4{\cdot}000 \times 10^{-3}$ and $b = -6{\cdot}0 \times 10^{-7}$. What temperature will the platinum thermometer indicate when the temperature on the gas scale is 300°C?

16. Describe how you would use *either* (i) a constant-volume *or* (ii) a constant-pressure air thermometer to calibrate a mercurial thermometer. If the difference of mercury level in a constant-volume air thermometer is -2 cm when the temperature of the bulb is 10°C and $+22$ cm when the bulb is at 100°C, what is the height of the barometer? (*L.*)