

1 The measurement of temperature

1.01 Introductory

The sense of touch enables us to assess in an approximate way the relative 'hotness' of bodies. Judgments made in this way are very unreliable however, as the sense of touch is a variable criterion and is not capable of distinguishing between the effects due to 'hotness' and the conductivity of the body. Thus due to the better conductivity of metals, a piece of brass or iron will seem colder to the touch than the wood of the bench on which it is placed. It is thus manifestly impossible to obtain a precise estimate of the 'degree of hotness' of a body by methods relying on sense impressions.

Physical science is largely concerned with the accurate measurement of quantities. Accurate experimental data is an essential pre-requisite for the development of theory, and at a later stage provides the means of checking and assessing the reliability of such theories. In that branch of physics dealing with the study of heat it is clear therefore that something better than the rough estimate of the relative 'degree of hotness', or *temperature* as it is called, is required than that provided by physiological sensations. The problem is therefore to construct a scale of temperature which shall be precise and consistent, and to devise a means of assessing the temperature of a body against this scale with a high degree of accuracy.

1.02 Temperature scales

In the construction of a temperature scale the first necessity is to choose two fixed temperatures, the interval between which is then divided into a number of small divisions each known as a 'degree of temperature'. The two fixed points chosen should be constant and easily reproducible at all times under specified conditions. The points previously chosen were the ice point (the equilibrium temperature between ice and air-saturated water at normal atmospheric pressure) and the steam point (the equilibrium temperature between liquid water and its vapour at the pressure of one standard atmosphere). These points were given the values 0°C and 100°C respectively thus defining the interval of the Celsius (centigrade) scale. Temperature determination on this scale was made by measuring the value of some thermometric substance (e.g., the volume of a given mass of mercury, pressure of a gas at constant volume, resistance of a piece of platinum wire, &c.) at the two fixed points and then at some other point the

temperature of which is required. If X_θ is the value of the property at this point, and X_0 , X_{100} the values of the property at the ice and steam points respectively, then the temperature $\theta^\circ\text{C}$ is defined by the relation

$$\frac{\theta}{100} = \frac{X_\theta - X_0}{X_{100} - X_0} \quad [1]$$

Although the Celsius temperature so defined may continue for some time in elementary teaching and everyday practice, it is replaced in the SI era by the *kelvin* (symbol K with no degree sign). The kelvin is the unit of the thermodynamic temperature scale (see section 12.07) and is defined as the fraction $\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water (i.e., that point at which the conditions of pressure and temperature are such that the solid, liquid and vapour phases of water co-exist in equilibrium). Thus, the kelvin scale tacitly assumes two fixed points, one of which is the triple point of water already stated, the other being the absolute zero of temperature. Hence, for the thermodynamic temperature T at any given point we have

$$\frac{T}{273.16} = \frac{X_T - X_{\text{abs. zero}}}{X_{tr} - X_{\text{abs. zero}}} \quad [2]$$

Where X_T , X_{tr} and $X_{\text{abs. zero}}$ are the properties of some thermometric substance at the given point, triple point of water and the absolute zero respectively.

As we have seen the determinant point on the thermodynamic scale is the triple point of water, its thermodynamic temperature (T_{tr}) being 273.16 K. The temperature of melting ice (T_{ice} , ice point, see above) on this scale is very slightly less than T_{tr} being 273.15 exactly. It should be emphasized, of course, that the degree Celsius ($^\circ\text{C}$) is a unit of thermodynamic temperature *interval* identical with the kelvin, and the statement of the 'temperature' of a body in degrees Celsius ($\theta^\circ\text{C}$) must be considered as a statement for the excess of the thermodynamic temperature (T) of the interest over that of melting ice (T_{ice}). Thus $\theta^\circ\text{C} = T - T_{ice}$. In this sense, therefore, we see that the absolute zero of temperature is exactly -273.15°C .

The practical realization of the conceptual thermodynamic scale of temperature is best brought about using a gas as the thermometric substance. It can be shown (see p. 271) that a scale of temperature based on the properties of an idealized gas is identical with the kelvin thermodynamic scale. Thus by measurements on the pressure of a constant mass of gas at constant volume, the thermodynamic temperature T is, from equation 2

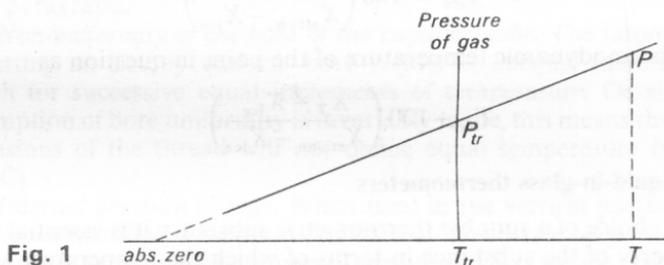
$$T = \frac{P_T - P_{\text{abs. zero}}}{P_{tr} - P_{\text{abs. zero}}} \times 273.16 \quad [3]$$

P_T , P_{tr} and $P_{\text{abs. zero}}$ being the pressures of the gas at the point in

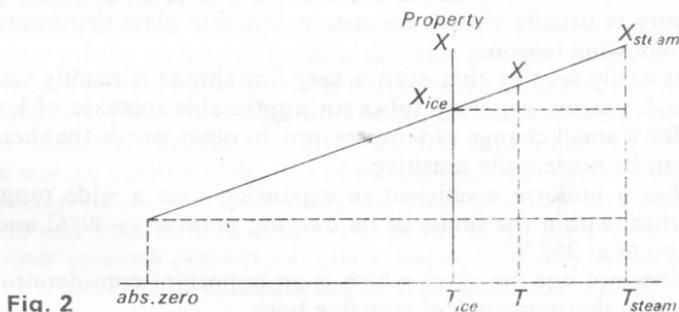
question, the triple point of water and the absolute zero respectively. Since the pressure of an idealized gas is zero at the absolute zero of temperature, the expression for temperature using such a gas thermometer may be given as

$$T = \frac{P_T}{P_{tr}} \times 273.16 \quad [4]$$

This is shown geometrically in Fig. 1 and it is clear that for such a thermometer the only standardizing reading needed is the pressure of the gas at the triple point of water, temperature then being measured by obtaining the pressure of the gas at the point in question and using expression 4.



Other thermometric properties can, of course, be used in the practical realization of temperature scales. For instance we can use the varying lengths of a metal rod, or the changes in volume of a given mass of mercury, to mention but two that are in everyday usage. It is clear that in such cases the measured property does not have a zero value at the absolute zero, nor is it possible to determine the required value at this point for insertion in equation 2 for the purposes of temperature evaluation. Accordingly, for *practical purposes*, it will be necessary to use an additional standardizing temperature in order to calibrate the thermometric instrument. This is shown geometrically in Fig. 2



where T_{ice} has been taken as a laboratory replacement of T_{tr} and the other standardizing temperature is that of the steam point (T_{steam} — see above). X_T , X_{ice} and X_{steam} are the measured values of the thermometric property X at the point in question, the ice point and the steam point respectively. From the geometrical properties of Fig. 2 it will be seen that

$$\frac{X_{\text{steam}} - X_{\text{ice}}}{T_{\text{steam}} - T_{\text{ice}}} = \frac{X_T - X_{\text{ice}}}{T - T_{\text{ice}}}$$

giving the excess thermodynamic temperature above the ice point (i.e. θ degrees Celsius) as

$$T - T_{\text{ice}} = 100 \left(\frac{X_T - X_{\text{ice}}}{X_{\text{steam}} - X_{\text{ice}}} \right) \quad [5]$$

or, the thermodynamic temperature of the point in question as

$$T_{\text{ice}} + 100 \left(\frac{X_T - X_{\text{ice}}}{X_{\text{steam}} - X_{\text{ice}}} \right)$$

1.03 Liquid-in-glass thermometers

In the choice of a suitable thermometric substance it is essential that the property of the substance in terms of which the temperature scale is to be defined, should be capable of exact evaluation at the fixed point(s). In addition, the property selected must vary uniformly with temperature over as wide a range as possible. The expansion of matter when heated, particularly the expansion of liquids, was first used for temperature definition. Thermometers were constructed in which the liquid, contained in a small thin-walled glass bulb, was capable of expansion along the fine bore of a thick-walled hermetically sealed capillary tube. With a tube of uniform bore the change in length of the liquid column is proportional to its expansion. If the length of the column is l_0 at the ice point, l_{100} at the steam point, the temperature at which the column has length l_t may then be obtained by the substitution of these measured quantities in expression 5 above.

Mercury is usually chosen for use in liquid-in-glass thermometers for the following reasons:

- (i) It is easily seen so that even a very fine thread is readily visible. With such narrow capillary tubes an appreciable increase of length results for a small change of temperature, in other words the thermometer can be made quite sensitive.
- (ii) It has a uniform coefficient of expansion over a wide range of temperature within the limits of its freezing point at -39°C and its boiling point at 357°C .
- (iii) It does not wet the glass, which is an important consideration in constructing thermometers of very fine bore.

- (iv) It is a good conductor of heat, and hence quickly takes up the temperature of the body.
- (v) It has a low specific heat capacity, and thus the thermometer bulb absorbs little heat.

1.04 The mercury thermometer: errors and corrections

Mercury-in-glass thermometers, though inexpensive and convenient to use, suffer from the following defects which limit their use for accurate scientific work. The errors arising from these defects vary with different thermometers, and will further depend on the type of glass used. An indication of the size of the errors is given in brackets at the end of each paragraph.

(i) *Non-uniformity of the bore of the capillary tube.* The impossibility of getting an exactly uniform bore results in unequal increments in length for successive equal increments of temperature. Or since the assumption of bore uniformity is invariably made, this means that equal extensions of the thread will not define equal temperature intervals (0.1°C).

(ii) *Internal pressure change.* When used in the vertical position (this error does not affect a thermometer used in the horizontal position) the hydrostatic thrust of the column of mercury causes a slight distension of the bulb. In consequence of this, readings registered by the thermometer in this position will be too low (0.001°C per cm change of pressure).

(iii) *External pressure changes.* The bulb suffers contraction due to the inward thrust of the liquid in which it is immersed, resulting in readings which are too high. Atmospheric changes also bring about errors of the same sort as those listed here and in (ii) above (0.001°C per cm change of pressure).

(iv) *Exposed stem correction.* Only when the full stem as well as the bulb of the thermometer are immersed in the heated liquid will the temperature of the mercury be the same throughout. When an appreciable length of the stem is exposed the mercury here will be cooled by an unknown amount, which will cause the thermometer to under-read. The error arising under this heading depends not only on the length of the exposed thread, but also on the temperature difference between the hot liquid and the surrounding air. The required correction to be added to the observed reading t is given by the expression $An(t-t')$ $^\circ\text{C}$, where n is the number of degrees of mercury column exposed and t' its mean temperature. A is a constant, the value of which varies between 0.00015 and 0.00016 according to the nature of the glass used.

(v) *Glass envelope corrections.* Glass responds slowly when subject to heat treatment. In consequence of this, a sudden cooling, as for example when a thermometer at room temperature is plunged into ice,

will produce a depression below the zero mark due to the failure of the bulb to contract quickly. The creep to zero may be a matter of several hours, different qualities of glass responding differently in this respect (0.01 to 0.05 °C).

A similar error, known as the *secular change*, may affect the ice point for a period of several years after the thermometer has been made. The very slow contraction of the glass bulb causes a slight rise at the ice point, which should be checked at periodic intervals to obtain the necessary zero correction (0.01 °C per annum).

1.05 Extensions of range

In practice the range of a mercury-in-glass thermometer is from temperatures somewhat above its freezing point at $-39\text{ }^{\circ}\text{C}$ to temperatures up to $300\text{ }^{\circ}\text{C}$. The upper limit of the range can be greatly extended however, by the introduction of some inert gas such as nitrogen in the space above the mercury. As the mercury expands the pressure of the gas is raised with consequent increase in the boiling point of mercury. In this way such a thermometer may be satisfactorily used for temperatures up to $600\text{ }^{\circ}\text{C}$.

The extension of the lower limit necessitates the replacement of mercury by other liquids. Alcohol (b.p. $78\text{ }^{\circ}\text{C}$) may be used to record temperatures down to its freezing point at $-114.9\text{ }^{\circ}\text{C}$, whilst the use of liquid pentane permits of a downward extension of the range to $-200\text{ }^{\circ}\text{C}$. It is important to note that alcohol thermometers and others with ranges that do not cover both the ice and steam points, cannot be graduated directly. In such cases it is necessary to standardize the thermometer by comparison with a mercury or other thermometer. Temperatures above $600\text{ }^{\circ}\text{C}$ or below $-200\text{ }^{\circ}\text{C}$, are not measured by liquid-in-glass thermometers.

1.06 The constant volume gas thermometer

It has been seen that on account of the uncertain behaviour of the glassy envelope, and for other reasons, the mercury thermometer is unreliable as an instrument for accurate work. With different specimens of glass having their own peculiar properties, it will be extremely unlikely that any two mercury-in-glass thermometers will record exactly the same reading at any given temperature. For standardizing purposes gas thermometers are now invariably used. These thermometers, employing a gas as the thermometric substance, are constructed for use either for measuring the pressure of the gas when contained at constant volume, or with the pressure constant to measure the volume changes. The former method has been found to be much the more convenient in practice, and as the two thermometers give identical temperature

scales for a gas obeying Boyle's law, only the constant volume instrument will be described here.

Among the main advantages of the constant volume gas thermometer over the mercury-in-glass thermometer may be mentioned the following:

- (i) Gases produce large proportionate increases of volume and pressure when heated, and in consequence gas thermometers are more sensitive, and the correction for the expansion of the envelope is relatively unimportant.
- (ii) Gases can be obtained in a high state of purity, and thus the thermometers are reproducible to the same degree of accuracy in whatever place they are required for use.
- (iii) They can be used to cover a very large range of temperature (see section 1.08).
- (iv) These thermometers give very close agreement with the thermodynamic scale of temperatures (see section 12.07).

Gas thermometers are however large and cumbersome for routine work, and can only be used in one position. Their important use is for the calibration of other thermometers such as the mercury, platinum resistance, or thermo-electric thermometers, which are more convenient to manipulate.

1.07 Jolly's constant volume gas thermometer

The simple type of constant volume gas thermometer due to Jolly is shown in Fig. 3. It consists of a bulb *A* containing a fixed mass of gas which is completely immersed in the body whose temperature is required. The bulb *A* is connected by narrow tubing *B* to an open

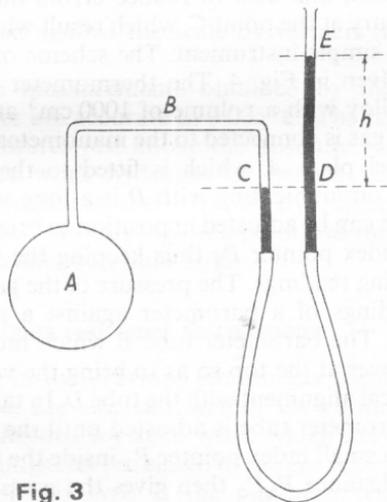


Fig. 3

mercury manometer. Since the gas contained in B is not at the temperature of the body, the bulb A should be of sufficiently large volume to reduce errors due to the 'dead space' in B . In using the instrument, the movable limb of the manometer is adjusted so as to maintain the level of the mercury at C . The pressure of the gas at constant volume is obtained by adding (or subtracting) the difference of mercury level (h) at C and E to the barometric height H , which should be taken at the beginning and again at the end of the experiment.

The temperatures defined by the constant volume gas thermometer are given by (taking the ice point as a convenient laboratory standard):

$$T = \frac{P_T}{P_{\text{ice}}} \times 273.15 \quad (\text{see section 1.02})$$

where P_{ice} , P_T are respectively the pressures of the gas at the ice point and at the temperature of the body. If the corresponding mercury level differences are h_{ice} and h_T , then the working formula for the thermometer will be

$$T = \frac{H + h_T}{H + h_{\text{ice}}} \times 273.15$$

1.08 The standard constant volume gas thermometer

This instrument, due to Chappuis, is an elaboration of Jolly's simple instrument, and is designed chiefly to overcome the inaccuracies in Jolly's instrument due to fluctuations in the barometric height in the course of the experiment, and also to reduce errors due to capillary depression of the mercury at the point C , which result when using tubes of narrow bore in the simple instrument. The scheme of the standard gas thermometer is given in Fig. 4. The thermometer bulb T , made of platinum-iridium alloy with a volume of 1000 cm^3 and a length of 110 cm containing the gas is connected to the manometer by a capillary tube C through a steel plate A , which is fitted to the wide tube D containing mercury. Communicating with D is a long vertical tube E and a reservoir R which can be adjusted in position to bring the mercury level in D to a fixed index pointer P_1 thus keeping the volume of the gas constant when taking readings. The pressure of the gas is measured directly from the readings of a barometer against a scale S whose zero is adjusted at P_1 . The barometer tube B which moves vertically in the tube E , is bent over at the top so as to bring the widened end of the closed tube in vertical alignment with the tube D . In taking a reading of the pressure, the barometer tube is adjusted until the mercury level is just in contact with a small index pointer P_2 inside the vacuum of the barometer tube. The distance P_1P_2 then gives the pressure of the gas

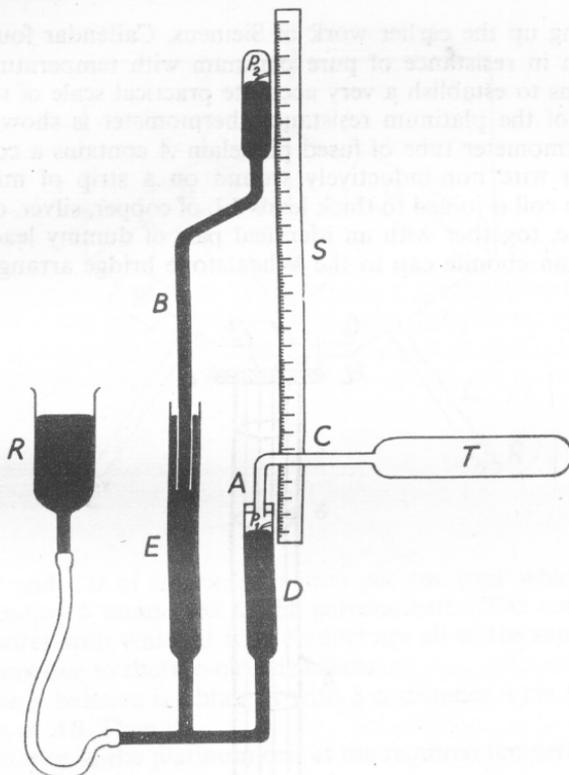


Fig. 4

which is read off against the scale by verniers (not shown) at P_1 and P_2 .

Temperature measurements obtained by the standard hydrogen gas thermometer are accurate to 0.005°C . The range of the instrument is from temperatures just above the absolute zero up to 1750 K. For low-temperature work hydrogen or helium gas is used (sometimes neon). At temperatures above 750 K hydrogen diffuses through the envelope, and for work at high temperatures nitrogen gas is used in a platinum or platinum-iridium bulb.

1.09 The platinum resistance thermometer

As indicated in the previous section gas thermometers, being cumbersome in use, are not satisfactory for routine work. Other thermometers are needed for such work which are easier to manipulate, and whose readings can be related to the gas scale. The most satisfactory thermometer of this type is the platinum resistance thermometer.

Following up the earlier work of Siemens, Callendar found that the variation in resistance of pure platinum with temperature provided the means to establish a very accurate practical scale of temperature. A form of the platinum resistance thermometer is shown in Fig. 5. The thermometer tube of fused porcelain *A* contains a coil *T* of fine platinum wire non-inductively wound on a strip of mica *M*. The platinum coil is joined to thick leads *LL* of copper, silver, or platinum, and these, together with an identical pair of dummy leads *L'L'*, pass through an ebonite cap to the Wheatstone bridge arrangement used

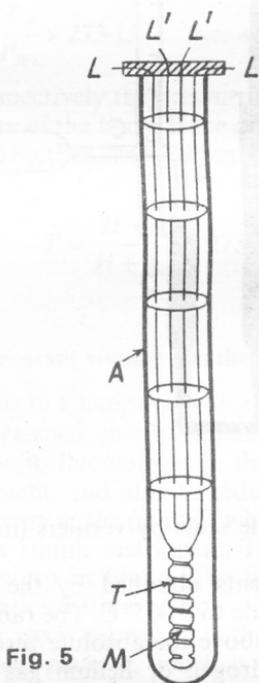


Fig. 5

for measuring the resistance of the platinum coil. A number of mica discs (five only shown) are placed in the tube to insulate the leads from one another, and also to prevent convection currents in the air of the tube.

A special form of Wheatstone bridge, devised by Callendar and Griffiths for use with the thermometer, is shown in Fig. 6. In this arrangement the ratio arms contain equal resistances *P* and *Q*. The dummy leads *L* with a variable resistance box *R'*, and the leads *L* attached to the platinum spiral *R* are connected into the other two arms as indicated. Between these resistance arms there are uniform resistance

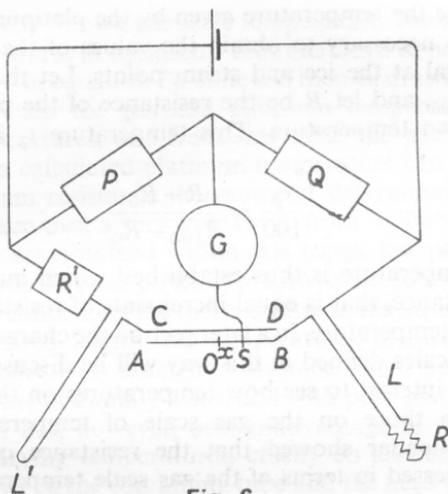


Fig. 6

wires AB and CD of resistance ρ ohm per cm, over which moves a sliding contact S connected to the galvanometer. The contact slider and the wires with which it is in contact are all of the same metal to avoid errors due to thermo-electric effects.

Suppose a balance is obtained with S a distance x cm from O the mid point of AB . Then if

R = resistance of the platinum coil at the required temperature,

L = resistance of the leads,

L' = resistance of the dummy leads,

l = length in cm of AO ,

$$\frac{R' + L' + (l+x)\rho}{R + L + (l-x)\rho} = \frac{P}{Q} = 1 \quad \text{Since } P = Q$$

$$R = R' + 2x\rho$$

Now the platinum chosen for the resistance coil must be of fine wire so that a reasonably high resistance can be obtained in a small space, and should be of such purity that the ratio of its resistances at the steam and ice points is not less than 1.386. Typical values for the coil are $R_0 = 25.6$ ohm with a fundamental interval of 10 ohm: A rise of 1°C will then cause a change of resistance of 0.1 ohm. If the wire AB has a resistance of 0.005 ohm per cm length, the movement (x) of S required to register this change is 10 cm, that is a movement of 1 mm corresponds to a change in temperature of $\frac{1}{100}^\circ\text{C}$. This indicates the order of accuracy with which readings of temperature can be made with the platinum resistance thermometer.

To calculate the temperature given by the platinum resistance thermometer it is necessary to obtain the values of the resistance of the platinum spiral at the ice and steam points. Let these resistances be R_{ice} and R_{steam} , and let R be the resistance of the platinum spiral at some unknown temperature. This temperature t_p is defined by the equation:

$$\frac{t_p}{100} = \frac{R - R_0}{R_{100} - R_0} \quad [6]$$

A scale of temperature is thus established which increases uniformly with the resistance, that is equal increments of resistance define equal increments of temperature. In a later section the character of the various temperature scales defined in this way will be discussed more fully. It is however of interest to see how temperatures on the platinum scale correlate with those on the gas scale of temperatures previously discussed. Callendar showed that the resistance of pure platinum could be expressed in terms of the gas scale temperature $\theta^\circ\text{C}$ by the following formula:

$$R = R_{\text{ice}} (1 + A\theta + B\theta^2)$$

where A and B are constants for the platinum wire and R and R_{ice} its resistance at the gas temperature θ and at the ice point respectively. The resistance R_{steam} at the steam point will then be given by:

$$R_{\text{steam}} = R_0 (1 + 100A + 10\,000B)$$

By substituting these values for R and R_{steam} in equation 6, an equation relating the platinum temperature θ_p to the corresponding gas temperature θ will be obtained. Thus:

$$\frac{\theta_p}{100} = \frac{A\theta + B\theta^2}{100A + 10\,000B}$$

from which

$$\theta - \theta_p = \frac{10^4 B}{A + 100B} \left\{ \left(\frac{\theta}{100} \right) - \left(\frac{\theta}{100} \right)^2 \right\}$$

$$\text{or} \quad \theta - \theta_p = \delta \left\{ \left(\frac{\theta}{100} \right)^2 - \left(\frac{\theta}{100} \right) \right\} \quad [7]$$

where
$$\delta = -\frac{10^4 B}{A + 100B}$$

The value of δ for pure platinum is very nearly 1.50, and the purity of the platinum used in the thermometer should be such that δ is not greater than 1.51. The value of δ is obtained by calculating the platinum temperature from equation 6 above using the measured resistance

value at an accurately known gas scale temperature. Insertion of these two related temperatures in equation 7 then enables δ to be determined. Using this value of δ in equation 7 a table can then be drawn up showing the difference between the gas and platinum temperatures against different gas temperatures, and from this table the gas temperature corresponding to a calculated platinum temperature can be obtained.

With the platinum resistance thermometer determinations of temperature can be taken over a very wide range from -200°C to 1200°C . Accurate readings are obtained within this range, but particularly so between 0°C and the sulphur point. It is convenient to use in practice, and since the leads connecting the thermometer to the measuring bridge can be of any desired length, the temperatures of furnaces can be conveniently and effectively taken at a distance. 'Stem' corrections are eliminated by the use of dummy leads, and with pure platinum there is no zero change. It has, however, one disadvantage in that it cannot register rapidly varying temperatures, chiefly on account of the low thermal conductivity of the containing tube and the need for balancing the bridge. The thermo-electric thermometer is well suited for this purpose and is described in the following section.

1.10 The thermo-electric thermometer

This thermometer depends upon the Seebeck effect, namely that if two dissimilar metals such as copper and iron are joined in series to make a complete circuit (Fig. 7), then on heating one of the junctions a current flows round the circuit. Such an arrangement is called a

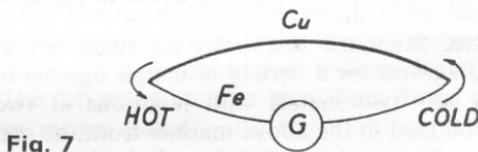


Fig. 7

thermo-electric couple, and the e.m.f. established round the circuit depends on the nature of the metals used to form the couple, and also on the temperature difference between the hot and cold junctions. The cold junction is usually maintained at the ice point, and it has been shown experimentally that when the other junction is at some temperature t , the thermo-electric e.m.f. set up depends upon the temperature according to the quadratic law:

$$e = A + Bt + Ct^2 \quad [8]$$

Where A , B , and C are constants depending on the metals used. This is shown graphically in Fig. 8. The temperature at which the e.m.f.

is a maximum (for the two metals) is called the *neutral temperature* t_N . It is more usual to represent the thermo-electric behaviour of two metals graphically by plotting their *thermo-electric power* P (that is the change in the thermo-electric e.m.f. per degree centigrade in temperature between the hot and cold junctions) against temperature. If t is measured from the ice point, the constant A is zero in equation 8 which becomes

$$e = Bt + Ct^2$$

Thus
$$P = \frac{de}{dt} = B + 2Ct$$

The graph of P against t is thus a straight line (see Fig. 9) cutting the temperature axis at the neutral temperature (for which $de/dt = 0$).

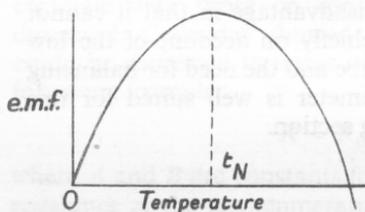


Fig. 8

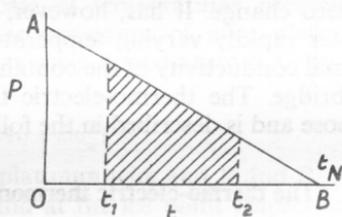


Fig. 9

From this graph the e.m.f., established when the junctions are at two temperatures t_1 and t_2 , is $e = \int_{t_1}^{t_2} P dt$, and is equal to the area of the

shaded portion shown. Standard textbooks on electricity give the thermo-electric line diagrams for a variety of metals against lead, the e.m.f. established for any two metals with junctions at two given temperatures being obtained in the above manner from the area intercepted between the two lines and the ordinates through t_1 and t_2 .

It can thus be seen that it is possible to determine temperature by the measurement of the thermo-electric e.m.f. set up across a calibrated thermocouple, one junction being kept at a fixed temperature whilst the other is maintained at the unknown temperature in question. For accurate work it is necessary to measure the thermo-electric e.m.f. using a sensitive potentiometer calibrated against a standard cell,* but for routine work where a high degree of accuracy is not required, it is sufficient to use a milli-voltmeter or a high resistance galvanometer connected directly across the two wires. A ballast resistance R (see Fig. 10) may be included in the circuit if the resistance of the recording

* See the author's book *A Laboratory Manual of Physics*—Arnold.

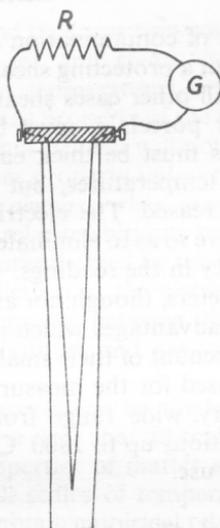


Fig. 10

instrument is not sufficiently great, so as to make the temperature resistance variation of the metal wires comprising the junction small compared with the total circuit resistance. Used in this way the recording instrument can be graduated to give direct readings of temperature after calibration.

From the previous outline of electrical theory it is evident that to avoid ambiguity in the readings of the thermometer, two metals must be chosen with a neutral temperature well outside the range of readings for which the thermometer is required. If in addition the thermo-electric lines of the two metals are steeply inclined to one another, increased accuracy of measurement will result for small temperature changes. The following couples have been found satisfactory for the temperature ranges stated:

Up to 300°C—Copper (or iron) against constantan (*Cu* 60, *Ni* 40). Such a couple give a comparatively large e.m.f. (see table 1), but is unreliable above the temperature indicated on account of oxidation troubles.

Up to 1100°C—‘Chromel’ (an alloy of chromium and nickel) against ‘Alumel’ (an alloy of aluminium and nickel).

Up to 1500°C—Platinum against platinum-rhodium or platinum-iridium. These latter couples have thermo-electric lines which are almost parallel, and so for an extended range give readings of e.m.f. which are approximately proportional to temperature differences. For this range the thermocouple, is calibrated by readings taken at the melting points of antimony, silver, and gold.

Provided there is no risk of contamination a thermocouple can be inserted in the source without a protecting sheath. Used in this way the 'time-lag' is very small. In all other cases sheaths of metal, or of high temperature fused silica or porcelain, must be used to protect the thermocouple. Such sheaths must be thick enough to withstand the mechanical strain at high temperatures, but not so thick that the 'time-lag' is appreciably increased. The electrical insulation of wires and leads must also be effective so as to eliminate any leaks which would introduce serious discrepancy in the readings.

Thermo-electric thermometers, though not as accurate as resistance thermometers, have several advantages which make them suitable for general industrial use. On account of their small thermal capacity and low 'time-lag' they can be used for the measurement of varying temperatures. They have a very wide range from -250°C to nearly 1600°C (with special precautions up to 1800°C), and in addition they are cheap and convenient in use.

Table 1 E.m.f. in millivolts of different thermocouples at the temperatures indicated—one junction being at 0°C

Temperature of hot junction in $^{\circ}\text{C}$	Copper-Constantan	Chromel-Alumel	Platinum-Platinum-Rhodium (10%)
100	4	4.1	0.64
200	9	8.1	1.44
300	15	12.2	2.32
400	—	16.4	3.25
600	—	24.9	5.22
800	—	33.3	7.33
1000	—	41.3	9.57
1500	—	—	15.50

1.11 Measurement of very high temperatures—radiation pyrometry

The measurement of temperatures beyond the upper limit of the thermo-electric thermometer is carried out by radiation pyrometers. These are of two types, (a) the optical type, (b) the total radiation type. Accurate readings are possible up to 3000°C and upwards by these instruments, which depend upon the laws of radiation. A detailed discussion of radiation pyrometers is deferred to Chapter XI.

1.12 Arbitrary nature of temperature scales

Temperatures are analytically defined with respect to some particular property of a substance as the proportionate change in the value of this property compared with the change between the two fixed

points (absolute zero and the transition point of water or, in laboratory practice, between the ice and steam points—see section 1.02). It necessarily follows that temperatures defined in this way will vary uniformly with the chosen property of the substance. Clearly, however, the temperature scale thus defined will not agree with a scale obtained in relation to some other property *unless the two properties themselves show identical relative changes when compared with one another*. In practice no such exact relationship has been found to hold good, and consequently temperatures defined by the expression of paragraph 1.02 are as numerous and distinct as the properties which define them. An instance of the discrepancy between the numerical evaluation of temperatures on the platinum and gas scales has already been given in section 1.09.

As no particular property can be singled out as being more fundamental than another it is clear that all scales of temperature defined in relation to specific properties of matter are arbitrary. It is of course possible to calibrate all scales of temperature with reference to one particular scale and to obtain empirical relationships between the other scales. In this way temperatures can be co-ordinated and systematized without however having any fundamental significance. The use of any such arbitrary scale as the standard scale is necessarily unsatisfactory, and it is clear that the ideal scale must be one which is not in any way dependent on any particular property of matter.

In chapter 12 it will be shown that an ideal scale can be conceived on thermodynamical grounds. This scale, due to Kelvin, has the theoretical advantage of specifying exactly the equality of temperature intervals, and defining an absolute zero from which all temperature measurements can be made. Unfortunately this scale cannot be realized in practice, but Kelvin showed that a scale based on the properties of a 'perfect' gas would be identical with the thermodynamic scale. All gases show departures in varying degree from the gas laws, and in consequence different gases give temperature scales which show deviations from one another. At low pressures, however, there is close agreement with the standard gas equation, particularly for the more permanent gases such as hydrogen and helium. Thus a scale of temperature defined by a gas thermometer containing hydrogen at low pressure gives the closest practical realization of the centigrade thermodynamic scale. For this reason the scale of temperature defined by the hydrogen gas thermometer is accepted as the standard scale to which all other scales are ultimately referred.