THE MEASUREMENT OF HIGH TEMPERATURES.

The subject of the measurement of high temperature is one which has had a very large influence on the whole commercial and industrial progress of the world and has to-day become of vital importance in nearly every branch of manufacture, and it is mainly due to the advance that has been made in the accuracy of high temperature measurements that we owe nearly the whole of the rapid progress in Modern Engineering and other Sciences.

The use of heat in the arts and sciences has been continued from very early times but no mention is made of any successful attempt to estimate any of the temperatures employed till such a late date as 1701, when Sir Isaac Newton made an effort to measure the temperature of a fire. The method he employed was to heat an iron bar in the fire and then withdrawing it and measuring the time it took to cool to an observed known temperature, as by this time the use of ordinary thermometers was known but their upper registering limit was low. The results Newton obtained were not in any sense accurate and the method was too clumsy for commercial purposes. In 1782 Josiah Wedgwood found that in his pottery making it was essential to measure the temperatures at which the clays, &c. were baked in order to get consistent results. He made use of the fact that clay on being baked, shrinks and he assumed that the shrinkage was directly proportional to the highest temperature obtained. Small cylinders of clay were used and heated and allowed to cool and their contraction measured by the distance which the cylinder would move along a sloping groove. The marking in degrees of the scale was purely arbitrary as all that was required was that cylinders of a uniform make should arrive at the same position in the groove for a given temperature and this method ensured that more or less consistent results were obtained. It was the sole type of pyrometer used for nearly 40 years and is in fact in use in some places to this day.

Wedgwood endeavoured to correlate the results he obtained with definite measurements in degrees Fahrenheit but he fell into the error of assuming a uniform contraction of the cylinder with increase of temperature and by this means he arrived at figures which are somewhat ludricrous. For instance he gave the melting point of wrought iron as being 21,637° F., whereas the present accepted value of this temperature is 2,770° F., a difference of nearly 19,000°.

In 1822 Daniell produced a pyrometer which was based on the expansion of a platinum rod embedded in a plumbago tube, one end of the rod was pressed against the end of the

tube and the other end was free to move, its movement being measured by a multiplying device which measured the expansion by a pointer on a dial. The scale on the dial was divided evenly as it was assumed that the difference between the expansion of graphite and platinum was uniform at all temperatures. With this pyrometer Daniell obtained a value of 2,233° F. for the melting point of silver whose true figure is 1,751° F., showing an error of only 482° F., a very great advance on Wedgwood's results. This pyrometer was widely used and it is in use to this day in another form, in bakers' ovens, where it consists of an iron rod surrounded by a porcelain or fireclay tube. But this type of pyrometer loses its accuracy owing to the fact that the coefficient of expansion of the material alters with prolonged heating and moreover the alteration is different for each substance.

All practical instruments for measuring temperatures are based on some physical change on the part of the substances employed—such as the alteration of volume of the mercury in the ordinary thermometer or the change in pressure volume on the part of a gas, &c., and so it is of the utmost importance that whatever principle is employed that all these measuring instruments should read alike at the same temperature, and so it is necessary that some standard independent of any physical property of matter should be used. Such a standard is the Thermodynamic scale of temperatures originally suggested by Lord Kelvin. This scale is based upon the conversion of heat to work in a heat engine, a process independent of the working substance, where existing instruments are compared with this standard it is found that if we make a scale of temperatures based on the oft quoted relation $\frac{P.V.}{T}$ = constant that this temperature is in close agreement with the Thermodynamic scale, and of course if the gas employed were "Perfect" the scale conformity would be exact. In fact it is found that gases such as Hydrogen, Nitrogen, or Air are all suitable to give indications about identical with the Thermodynamic scale.

The most convenient method in practice is to make use of the Constant Volume Gas Thermometer. It is not proposed to describe such a thermometer in detail as it is an instrument which can only be used with extreme care and with many very delicate corrections. But it is the standard against which all other forms of pyrometer are calibrated. By using bulbs of radio platinum, temperatures exceeding 900° C. can be measured, though the maximum so far reached with a gas thermometer is in the region of 1,550° C., but it is very necessary that further experiments should be carried out to extend the range of the gas thermometer to 2,000 or more so that high reading pyrometers can be checked directly against the gas scale.

TABLE I.—TABLE OF FIXED POINTS.

Substance.	Physical Condition.	Deg. Cent.	Deg. Fahr.
Water (ice)	At Melting Point	0	32
Water	„ Boiling „	100	212
Aniline	„ „ „	184	363
Naphthalene	„ „ „	218	424
Tin	„ Melting „	232	449
Lead	„ „ „	327	620
Zinc	„ „ „	419	786
Sulphur	„ Boiling „	445	833
Antimony	„ Melting „	631	1,167
Aluminium	„ „ „	657	1,214
Common Salt	„ „ „	800	1,472
Silver (in air)	„ „ „	955	1,751
Silver (free from oxygen)	„ „ „	962	1,763
Gold	„ „ „	1,064	1,947
Copper (in air)	„ „ „	1,064	1,947
Copper (graphite covered)	„ „ „	1,084	1,983
Iron (pure)	„ „ „	1,520	2,768
Palladium	„ „ „	1,549	2,820
Platinum	„ „ „	1,755	3,190

The gas thermometer has been used to accurately determine certain so-called fixed parts by which other instruments may be calibrated conveniently and Table I. shows such a table giving a list of substances with their melting or boiling points in degrees Centigrade or Fahrenheit. It will be noticed that these substances are all such as can be obtained in the absolutely pure condition and this is essential as the presence of relatively small amounts of impurities will give rise to serious errors.

It is not yet possible to compare an instrument directly with the gas thermometer above 1,550° C. so that higher temperatures must be arrived at by extrapolation. By careful observation of a physical change at temperatures up to 1,550° C. the law governing such change may be discussed and assuming the law to hold indefinitely higher temperatures may be deduced mathematically, but in any case of extrapolation there is uncertainty *vide* Wedgwood's results.

The laws governing the radiation of energy at different temperatures appear, however, to be capable of mathematical proof from Thermodynamic principles and so temperatures thus obtained are in reality expressed in the Thermodynamic scale and so extrapolation of these laws to deduced temperatures by means of Radiation Pyrometers appears to be justified, but it is still desirable that they should be checked by the gas scale.

We will now discuss the general principles of Radiation Pyrometers and their practical application. Any substance with a temperature above absolute zero (— 273° C.) radiates energy to its surroundings by means of waves. Below 400° C. these

waves produce no impression on the retina of the eye and the body therefore appears dark, above 400° C., however, visible rays begin to be emitted and as the temperature rises the body increases in brightness, the difference between the non-luminous and luminous wave lengths being merely that of length, the shorter wave lengths being visible but all wave lengths represent Radiant energy. In addition to giving out radiant energy a substance always receives waves from its surroundings which it absorbs or reflects, those it absorbs tending to raise its temperature. The rate at which a substance emits or absorbs radiant energy depends on the nature of its surface, a rough black surface radiates and absorbs heat with greater ease than any other while a polished metallic surface which acts as a reflector is the worst. But even a surface of finely divided soot does not completely absorb all the waves which fall on it but reflects a small proportion. If we could find an " absolute black surface " it would be totally devoid of reflecting power and would absorb all the energy reaching it but no such surface is known but Kirchoff has shown that it is possible to devise an arrangement which will give the same numerical results for energy radiated as would be obtained by the perfect black surface and such an arrangmeent is termed a " Black Body " and the radiates from it are called Black Body Radiations. Such an arrangement is obtained if we have a heated mass enclosed all round in a box with a small hole in one place in the side of the box, and it can be proved that no matter what the surface of the heated mass be like, *i.e.*, either polished or black, the amount of energy which escapes through the opening must be the same and only dependent on the temperature of the body. This condition is obtained in the case of a block of steel in a furnace at constant temperature and moreover black body radiations can always be secured by placing a tube closed at one end in the heated space and receiving radiations through the open end, so that all that is required is an instrument for measuring temperatures based on Black Body Radiations and such is obtained in the Radiation Pyrometer. The design of the Radiation Pyrometer depends on the law connecting the energy radiated by a substance, under given conditions, with its temperature. This was first accurately stated by Stefan in 1879 from data supplied by Tyndall. He concluded that the energy radiated by a given solid varied as the fourth part of its absolute temperature. This was soon found not to hold true for all instances but in 1884 Boltzmann showed from Thermodynamic Principles that the quantity of energy radiated in a given time from a Perfect radiator (or black body) must vary as the fourth power of its absolute temperature and it is from the now named Stefan-Boltzmann law that Radiation Pyrometers are based.

Expressed in symbols the fourth Power law takes the form of

$$E = K\,(T_1^4 - T_2^4)$$

where E is the total energy radiated.

T_1 is the absolute temperature of the Black Body.

T_2 is the absolute temperature of the receiving substance.
K is a constant depending on the units chosen.

If E is expressed in calories per cm^2 per second the value of K is $1 \cdot 34 \times 10 - {}^{12}$.

It will be noted that if the temperature of the receiving body were zero (absolute) the energy leaving the black body would be KT^4 whereas if T_2 is equal to T, the loss of energy would be nil as no substance can cool by radiating to a lower temperature than its surroundings.

So that from the above when the relation between the temperature and quantity of energy radiated is known in any units any instrument which will indicate the amount of the radiations it receives may be used to measure temperatures. The ray from the black body for example may be focussed on a thermal junction which will be heated according to the amount of energy incident upon it, and when corrected to a millivoltmetre will cause deflections proportional to the energy it receives.

In 1902 Fery introduced a pyrometer in which the rays were focussed by a lens upon a small blackened thermal junction, but this was not satisfactory owing to a variable proportion of the rays being absorbed by the lens itself, and in 1904 Fery overcame this by using a concave mirror to focus the rays, thus overcoming the error due to the absorption of the lens.

FERY'S MIRROR PYROMETER.

This instrument is shown in Fig. II. A concave mirror M which has a gilt reflecting surface is placed at one end of a metal tube and is fastened to a rack which engages in a pinion moved by the milled head P, so by turning P a longitudinal movement is imparted to the mirror. A small blackened thermal junction,

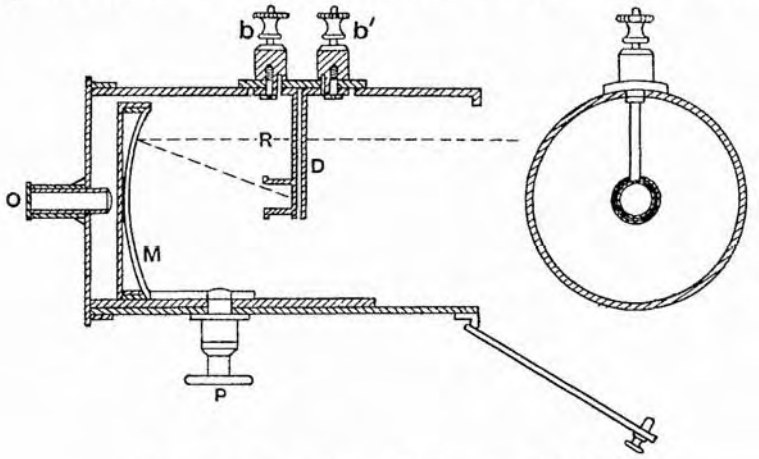

FIG. II.—Féry's Mirror Pyrometer. Section.

shown at the centre of the cross section, and consisting of a copper disc to which wires of copper or iron and constantan are fastened,

receives the rays, after reflection it may be brought into focus by suitably moving the mirror, the wires pass to the two terminals *b* and *b'* outside the tube from which leads are taken to the indicator. In order to discover when the junction is in the exact focus of the mirror an eyepiece *O* is fitted in the end of the tube which enables the junction to be seen magnified through a hole in the centre of *M*. By means of an optical device placed near the junction the image of the sighted object produced by *M* is reflected in two portions in the eyepiece *O*. When the junction is exactly in focus a circular image is seen round the junction, when out of focus the appearance presented is that of two semi-circles displaced laterally, it is adjusted by moving the mirror. A diaphragm is fitted at the front end of the Pyrometer in order that the opening may be partially closed by the diaphragm or left open as required, the diaphragm cuts off a definite proportion of the rays, it is used for very high temperatures and on the indicator two scales of temperature are provided one referring to full and the other to partial aperture. The proportions of the instrument are such that the junction never rises above 110° C. although the intensity of radiations diminishes as the square of the distance, the quantity impinging on the junction is, within limits, independent of the distance. This arises from the property of concave mirrors with respect to the relation between the size of an image and the distance of the object producing it, and it can be proved that the amount of energy received by the junction does not vary provided that the image produced overlaps the junction and that the limiting distance at which a correct reading can be secured is that at which the size of the image is equal to that of the junction, and in the case of practical instruments this distance is circa 30 feet.

FOSTER'S FIXED FOCUS RADIATOR PYROMETER.

The necessity of focussing which is common to all Fery's Pyrometers is obviated in Foster's instrument, which, however, cannot be used from so great a distance. The principle employed in the fixed focus instrument is that the amount of energy received by a concave mirror and focussed on a thermal junction will not vary so long as the area of the surface sending the rays to the mirror, through a fixed opening, increases as the square of the distance. This is explained from Fig. III.

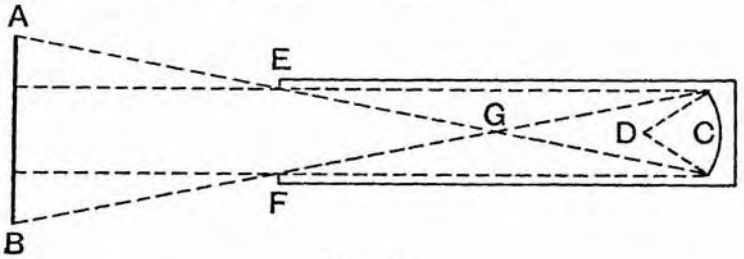

FIG. III.

C is the mirror, D a thermal junction fixed so as to be in the focus of the opening EF, and AB the heated surface. The lines joining E and F to the edge of the mirror intersect in a point G, and provided the lines GE and GF, if produced, fall within the heated surface AB, the quantity of energy falling on D will always be the same. A cross section of the cone GAB is a circle, and if AB be twice as far away from G as EF the areas of the circles of which AB and EF are diameters will be in the ratio 4 to 1. But as AB is twice as far from G as EF the intensity of its radiations will be as 1 to 4, and so the loss of radiating power is exactly balanced by the increase in area. In the actual instrument the tube in which the mirror is placed is blackened internally to cut out reflection, the diameters of the opening EF and the mirrror C are such that the perpendicular from G to AB is ten times the length AB, hence if the heated object is 6 inches in diameter the limiting position of G is $10 \times 6 = 60$ inches, the position of the Point G is indicated by a Ring outside the tube, and in taking a measurement the tube is brought well within the distance prescribed, which is in all cases 10 times the diameter of the heated object, temperatures are read by a portable Galvanometer attached to the thermal junction.

Having mentioned in discussing the Radiator Pyrometer that the radiant energy was measured by a thermo couple, we now turn to another class of pyrometer, *i.e.*, those of the thermo-electric type. The preliminary work on these was started by Seebeck in 1822, but it was not till 1886 that Le Chatelier successfully overcame the difficulties and produced a workable pyrometer. Although, if we take any two dissimilar metals and heat the junction between them we find that an electromotive force is set up at the junction, yet it does not follow that any metals will do for the purpose of measuring temperature.

For this purpose the following conditions must be satisfied :—

(1) The E.M.F. developed by the junction should increase regularly and uniformly as the temperature rises—as an instance of this, if we take a junction of iron and copper they will give rise to an E.M.F. which rises with the temperature to a certain point beyond which the E.M.F. falls off and finally reverses in direction although the temperature is rising all the time; these metals are therefore obviously unsuitable.

(2) The melting point of either component should be well above the highest temperature to be measured. An exception to this occurs when the E.M.F. of fused materials is employed.

(3) The thermo-electric value of the couple should not be altered by prolonged heating.

(4) The metals should be capable of being drawn into homogeneous wires so that a junction wherever formed may always give rise to the same E.M.F. under given conditions

It is a further advantage if the metals should be cheap and durable.

It must be remembered that *any* junction of two metals gives rise to an E.M.F. If we can take two wires and join one pair of ends and lead the wires direct to the galvanometer then the galvanometer will measure the E.M.F. generated by the heated junction, but in general these wires are expensive and it is impracticable to use them in this way so short lengths of wires are used, and these are connected by ordinary copper wire leads to the galvanometer, and we now find we have three dissimilar junctions, one from two metals *A* and *B*, one of *A* to copper and one of *B* to copper. Now *A* to copper and *B* to copper do not necessarily give rise to the same E.M.F. at the same temperature, but at one temperature the difference in E.M.F. can be known (note the E.M.F.'s will be in opposition and will tend to cancel each other), and so it is of the utmost importance that the cold junction should be kept at a steady known temperature; this point will be mentioned later.

A very useful point in connection with these junctions is that the E.M.F. developed is independent of the thickness of the wires —and, also, if the two wires are brought into contact, they may be fastened over the joint by soldering or by using a thick metal without alteration of thermo electric value except in rare cases. Until recently it was customary to use a platinum-rhodio platinum junction for all temperatures beyond the scope of the mercury thermometer, but the enormous price of these metals has brought into use fused metal couples which can be used with perfectly good results for temperatures up to about 1,000° C.; above this temperature platinum alloys are still used, but advance is being made in the use of fused metal couples.

Fig. V shows a section through a practical thermo couple. *J* is the hot junction and the wires for this are passed through

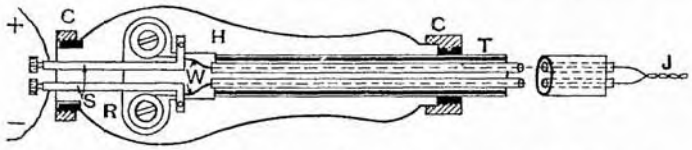

FIG. V.—Practical Form of Thermo-electric Pyrometer.

thin fireclay tubes which serve as insulators to the reels *RR* in the head, upon which a quantity of spare wire is wound to enable new junctions to be made if required, two brass strips *SS* are secured to the wires at one end and are furnished with screw terminals for the attachment of the galvanometer wires. A protecting tube *T* surrounds the wires and the hot junction, the head *H* may be constructed of wood, fibre or porcelain and should be an insulator for electricity and heat. In order to guard against errors arising from alterations in the temperature of the cold junctions it is sometimes useful to employ a water-cooled head as shown in Fig. VI. The choice of the protecting tube is

one of great importance; obviously it is required not to soften at the highest temperature attained, and when the junction is of

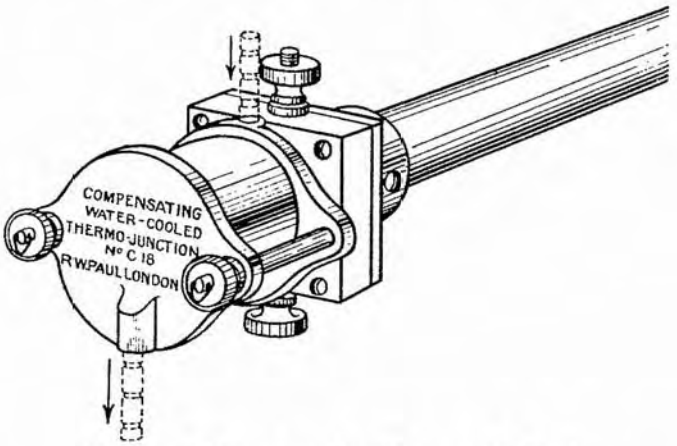

FIG. VI.—Pyrometer with Water-cooled Head.

expensive metals the sheath should not be permeable to gases or vapours; at the same time the sheath must be a good conductor of heat so that the junction may respond quickly to any change of temperature and it should be mechanically strong. Various substances are employed, each having special advantages and disadvantages. Mild steel is much used for temperatures not exceeding 1,100° C., but they are apt to deteriorate rapidly due to oxidation. Nichrome is also suitable but more expensive but lasts better. Molybdenum is unattacked by most molten metals and is very strong. Vitrified silicon is often used but is porous. Carborundum has proved useful for temperatures up to 1,600° C., and many other substances have been used at different times. It has been found that the continuity of the E.M.F. produced by the couple is not affected by the fusion of one or both of the elements forming the couple, and Fig. VII shows a form of Pyrometer

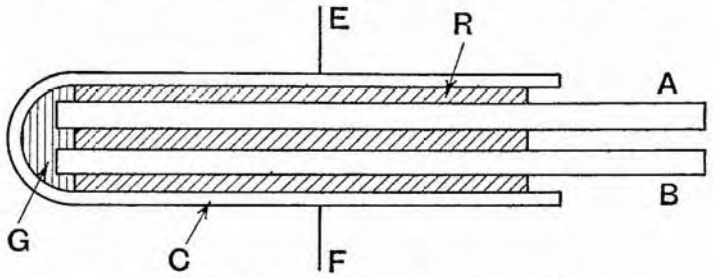

FIG. VII.—Liquid-element Thermocouple.

based on these lines. A rod of refractory material *R* is perforated with two holes down which are passed the rods of the thermo-elements *A* and *B*, the lower ends of *A* and *B* are inserted in a

graphite block *G*, which is jointed on its upper face to *R*, the whole being surrounded by the sheath *C*. On either or both of the elements melting the circuit is maintained through *G* which serves also to prevent the mixing of *A* and *B* when molten and at the same time it does not affect the E.M.F. developed. Up to the present it has not been found possible to procure the refractory parts in a form suited to commercial use, but this should be able to be overcome, in which case this type of couple should prove invaluable for measuring temperatures beyond the scope of the present forms. As the E.M.F. of the thermo-couple is small, being of the order of five millivolts for a rise of temperature of 100° C., a very sensitive form of galvanometer is needed, in which the E.M.F. is measured by the movement of a small mirror actuated by the coil of the armature working against a fine spring, the measurement being accomplished by the movement of a beam of light reflected by the mirror on to a scale. Various forms of Galvanometer are used, and it is worthy of note that the best metal couples have the advantage that they develop a higher E.M.F. per 100° C. rise in temperature than the noble metal couples, and so a coarser and less delicate type of galvanometer may be used (Pt. Pt. R. 1·1 mv. Iron Constantan 6·7 mv.).

These deflections are required to be read as degrees of temperature, and to enable this to be done it is necessary to construct a calibration curve; this is done by carefully placing the Pyrometer so that it shall measure some known temperature, the while being particularly careful that the cold junction is kept constantly at the temperature it is likely to attain when actually at work in practice. For the known temperature any of the fixed points shown in Fig. 1 may be used, and where possible points should be chosen so that the desired range of reading of the instrument shall lie within the readings of fixed points, thus avoiding extrapolation. As a rule the points chosen are the boiling point of water, the melting points of tin, zinc, and antimony, common rock salt and copper covered with graphite at its melting point, this latter being at a temperature of 1,084° C. These temperatures are plotted against the deflection of the galvanometer and a graph drawn as shown in Fig. 9, line *A* connects deflections with the corresponding differences between the temperatures of the hot and cold junction, so that the true temperature is given by adding the temperature shown on the graph to the temperature of the cold junction; this obviates the necessity for keeping the cold junction at any definite temperature. Line *B* represents the calibration of another pyrometer and is such that direct readings are obtained from any deflection for a cold junction temperature of 25 °C.; this is the type of curve obtained from the thermo-couple shown in the previous figure.

Permanent temperature scales can be made from these curves to attach to the galvanometer scale; if the calibration curve is nearly a straight line then divisions representing 100° C.

may be marked out, but if the line curves much then every 50 degrees or less must be marked on the galvanometer. It

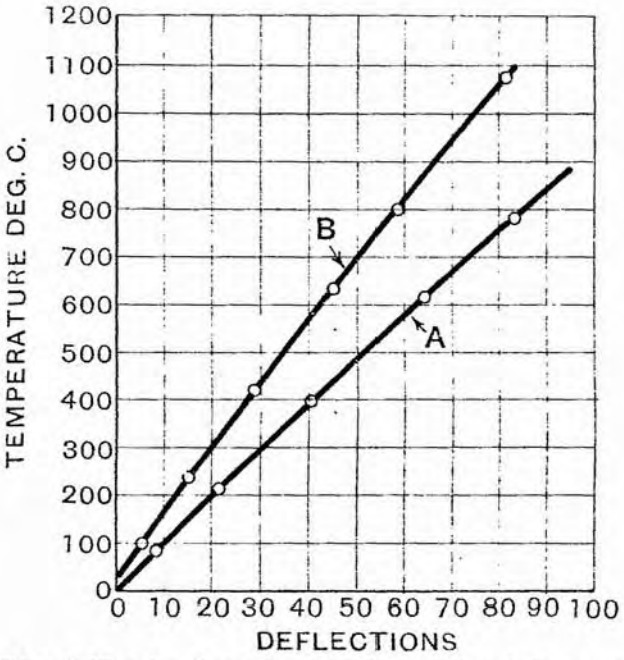

FIG. IX.—Calibration Curves for Two Thermo-electric Pyrometers.

is hardly necessary to add that the substances used for standardisation should be pure, as impurities will tend to lower the melting points. In one type of continuous recording pyrometer a mirror type of galvanometer is used, and a spot of light is directed on to sensitised bromide paper attached to a rotating drum which is set to rotate say once for 12 or 24 hours. This is a very sensitive instrument due to the use of mirror galvanometer, but has the disadvantage that the record is out of sight until developed in a dark room. For most commercial purposes a less sensitive and more robust instrument is used, which in effect consists of a galvanometer needle which at certain definite intervals of time is pressed on to an inked thread, thereby making an ink dot on a rotating drum of paper, thus giving a continuous and visible record. A further development is in the control of gas fired or electric furnaces. Should the temperature rise during a given interval the contact of the galvanometer needle with a stop will set relays in action and thereby lower the supply of gas or fire, and equally raise it if desired. By these means a furnace can be kept working between small limits of temperature. These instruments are more or less in their infancy, but indubitably have a great future.

Fig. 11 is shown as indicating a means of obtaining a differential cooling curve, that is of the difference of the rate

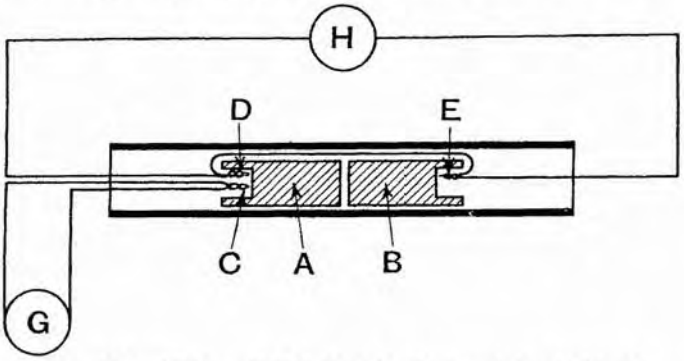

FIG. XI.—Differential Method for Determining Critical Points of Steel.

of cooling of two specimens in the same furnace. This is the means employed in a laboratory to measure small evolutions of heat during the cooling of say pure iron. These observations of critical temperatures are frequently of great service in deciding the subsequent heat treatment of an alloy steel. The sample of steel *A* is placed side by side with a piece of nickel *B* of equal dimensions in the tube of an electric furnace. A naked junction *C* is placed in a hole drilled in *A* and is connected to the galvanometer *G* which is calibrated to read temperatures. A two-junction circuit formed of a junction *D* placed in the hole *A* and another junction *E* located in the hole in *B* are connected to a delicate galvanometer *H*. The furnace is heated till the galvanometer *G* reaches say 900 degrees and then is allowed to cool. As *A* and *B* under normal circumstances cool at an equal rate, the junctions *D* and *E* will be at the same temperature, and so no deflections will be observed on *H*, when, however, owing to recalescence the cooling of *A* is arrested, *B* not being thus affected will continue to cool, thus producing a difference between the temperatures of *D* and *E* and consequently a deflection on *H*. The temperature of *A* at the time this occurs can be read off on *G*.

The advantages of the thermo-electric method of measuring temperatures compared with other methods are as follows :—

(1) Simplicity, no special experiment being needed to take a reading.

(2) Cheapness of outfit.

(3) Adaptability to a variety of purposes.

(4) Ease of repair in case of damage.

(5) Robustness, not being liable to get out of order under workshop conditions.

(6) Suitability to the purpose of a centrally controlled installation.

The drawbacks are :—

(1) Liability to error owing to fluctuation in the cold junction temperature (which may be avoided with care).

(2) Lack of sensitiveness at very high temperatures compared with the resistance method, a point seldom of great practical importance as the limit of accuracy is usually within the amount by which an ordinary furnace fluctuates under working conditions.

RESISTANCE PYROMETERS.

When a pure metal is heated its electrical resistance increases progressively with the temperature. This fact is made use of for the measurement of high temperatures. The choice of a metal in this case is more greatly restricted than in the selection of metals for a thermal junction, owing to the fact that a small alteration in size produces a very marked effect on the resistance of a wire. Also it is essential that there should be an entire absence of any internal physical change affecting the resistance. For temperatures above red heat the only feasible metals to use are platinum or the more expensive metal of the platinum series, and platinum is in general the metal employed. It is essential therefore to consider the effect of temperature on the resistance of this metal. Professor Callendar has thoroughly investigated this subject and evolved a formulæ from which the temperature of a given kind of platinum could be reduced with great accuracy from its resistance. This formulæ is :—

$$t - p = k\left(\frac{t}{(100)^2} - \frac{t}{(100)}\right)$$

where t is temperature on the gas scale;

p is the temperature on the platinum scale;

k is a constant depending on the purity of the wire.

The degrees on the platinum scale referred to are obtained by assuming that the increase of resistance of platinum is uniform at all temperatures. That is that the temperature resistance curve is a straight line and not, as it actually is, a parabola. In order to determine k it is necessary to measure the resistance of the wire at 0°C., 100°C. and a third temperature which should be considerably above 100°C. The first two readings establish the platinum scale of temperature and the third determines the value of k. p and t are equal at 0 and 100; these points form the basis of both scales.

Example :—a platinum wire has a resistance in ice of 2·6 ohms, in steam 3·6 ohms and in boiling sulphur 6·815 ohms. To find the value of k the boiling point of sulphur being 444·5 degrees on the gas scale.

Since an increase of (3·6—2·6)=1 ohm is produced by 100° C. the increase observed in boiling sulphur (6·815—2·0)

—4·215 ohms will represent a temperature on the platinum scale of

$$\frac{4 \cdot 215}{1} \times 100 = 421 \cdot 5^{\circ} p$$

Applying Callendar's formulæ,

$$(444 \cdot 5 - 421 \cdot 5) = k \left(\frac{444 \cdot 5}{(100)^2} - \frac{444 \cdot 5}{(100)} \right)$$

the value of k is found to be 1·5.

Great precision is needed in taking these initial readings. as in the example above if the boiling point of sulphur were taken 2 degrees lower, k would work out at 1·37 and the error at 1,200°C. would be about 17°C. And the same error would be caused if the resistance in boiling sulphur were taken as 6·835 ohms or an error of ·02 ohms so that most elaborate precautions must be taken for these initial readings or the final reading will be largely in error. Unless this can be done an operator would be well advised to standardise a resistance pyrometer by taking several fixed points and drawing a calibration curve as for a thermo-electric pyrometer.

A typical resistance pyrometer is shown in Fig. 12, where the coil of platinum wire is shown wound round the edges of a mica framework made of two strips of mica forming an X

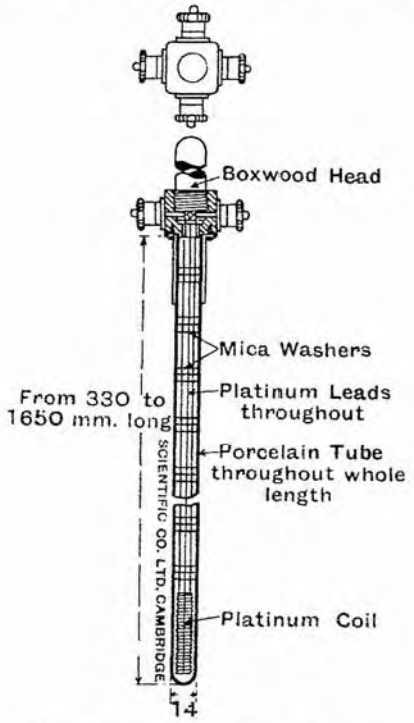

Fig XII.—Platinum Resistance Pyrometer.

as it is found that mica is chemically inert to platinum even at high temperatures. The platinum leads pass from the coil through mica washers to terminals in the boxwood head. A second wire not connected with the coil, but identical in length to the leads, is bent into two parallel branches which are passed through the mica washers side by side with the leads and are brought to a second pair of terminals in the head. This second wire compensates for changes in the resistance of the leads when heated, by opposing the compensating wire against the pyrometer in the measuring arrangement, when the resistance of the leads and the wire, being equal and opposite, will cancel, the resistance actually measured being that of the coil only. The resistance of the coil is measured by some adaption of the Wheatstone Bridge method.

There are many pyrometers of this type differing only in the method of supporting the coil, measuring the resistance, &c. In all cases the coil is wound non-inductively. This form of pyrometer may be used with varying forms of indicators, all of which are in reality outfits for the measurement of resistance but calibrated in degrees of temperature.

These pyrometers are not suitable for the continuous measurement of temperatures above 900°C., and even so the resistance gradually changes even when 900°C. is not exceeded, so readings should be continually checked by a fixed point in the neighbourhood of the working temperature. Generally speaking any serious defect entails returning the instrument to the makers, as a special degree of skill is required to repair them. The following are the advantages and disadvantages of this type of pyrometer.

It is more accurate than the thermo-couple for the measurement of steady temperatures below 1,000°C.

The readings are independent of the resistance of the wires used to connect the pyrometer and the indicator, as these are duplicated and so cancelled.

In addition, the head of the pyrometer may vary in temperature to any extent without affecting the result.

On the other hand they are more costly, more fragile, much more difficult to repair, and need much more skill and attention, and so are liable to get out of order when used industrially. But they are very suitable for certain classes of work when used in a laboratory.

OPTICAL PYROMETERS.

We now turn to a type of pyrometer which is analogous to the radiation type previously described. The principle is based on the fact that when a solid is heated above about 470°C. it begins to send out luminous radiations. As the temperature rises the luminous radiations become more intense and the colour of the body changes from a dull red to a lighter red, then to orange, yellow, white and, finally, to a dazzling white. Many attempts have been made since 1836 to assign

definite temperatures to specified colours. Howe's table is one of the latest of these, but of course it must be realised that it is quite impossible to accurately define these temperatures as no two observers can exactly detect the same colours at the same temperatures and even below a yellow heat two observers may be as much as 50 degrees apart, while when a dazzling white is reached accurate discrimination is impossible. At the same time it must be noted that a trained workman, working on one class of job, say the quenching of steel at 850 degrees, often acquires a high degree of judgment and may not vary by more than 15 degrees C. from the required temperature. But in general the personal equation is too great for colour judgment by the unaided eye to be taken as an accurate guide to temperature. But a fairly close approximation may be obtained by matching the colours against prepared standards.

The main types of Optical Pyrometers fall under the following heads :—

(1) Photo-metric type, in which the standard light is constant and the intensity of the light from the source is varied in the instrument until equal to the standard.

(2) Photo-metric type in which the standard is varied until equal to that of the source, which may be reduced in intensity if this exceeds that of the standard.

(3) The colour of the source is matched against a standard colour made to agree with that obtained in a given operation. Or the source may be made to produce a standard colour by a polarising device. Or the colour of the source is extinguished by suitable absorbents.

As regards the first two types the law connecting the intensity of the whole of the light waves emitted, with the temperature, for a given solid is approximately given by Rasch's formulæ—

$$\frac{I1}{12} = \left(\frac{T1}{T2}\right) x,$$

where $I1$ and 12 are the intensities corresponding to absolute temperatures $T1$ and $T2$, and the exponent $x = \frac{25{,}000}{T1}$. Hence at 1,250 degrees Abs. the brightness increases as the twentieth part and at 2,500 as the tenth part of the temperature. This rapid increase in brightness for a small rising temperature enables small increments to be readily observed. But in practice it is found there are vast differences in the brightness displayed by different substances at the same temperature, *vide* a gas mantle and a piece of platinum at the same temperature. It is possible, however, to obtain indications for any substance in terms of a black body. Thus if a heated solid possessed the same intrinsic brightness as a black body at a temperature of T the "apparent" or "black body" temperature of the

solid would also be called T. This would only mean that the light radiating from the solid was equal in intensity to that emitted by a black body at temperature T and to obtain the true temperature of the solid the temperature must be multiplied by a factor which expresses the ratio of its emissive power to that of the black body.

In all the photo-metric methods a standard light is employed which is kept constant in brightness and with which the light from the desired source is compared. No attempt is made to measure the candle-power of the illuminant. It is desired only to bring the standard and the source to the same degree of brightness. Amongst the standards employed are Carbon filament electric lamps, amyl acetate lamps, or the centre of an acetylene gas flame, each of which is capable of producing a fixed degree of brightness when used under standard conditions. The standard is then compared with a black body at known temperatures, thus furnishing a scale of black body temperatures. It is, however, found that above 1,000°C. the light becomes too dazzling to enable a proper comparison of the standard and source to be made, and so absorbing glasses must be used to reduce the brightness.

It is not possible to use any coloured glass, only a monochromatic glass is suitable, *i.e.* a glass which transmits light of one wave-length only.

As these pyrometers are required for use at temperatures above 1,000°C. it is necessary to consider the relation between the wave-lengths of light and the temperature of the radiating substance, which will be assumed to be a black body.

Wein has produced a law connecting the black body temperature and the intensity of a ray of wave-length which is as follows :—

$$J = c, \frac{-5}{\lambda} \times e \frac{-c2}{\lambda T}$$

where J =energy corresponding to wave-length;
e =base of natural logarithms;
T =absolute (thermo-dynamic) temperature of the black body;
c and $c2$ are constants the values of which may be found by measuring
J at two known temperatures for a light of known wave-length.

For the purpose of optical pyrometry a red light of wave-length of about 65 millionths of a centimetre may be used, and Wein's law may be applied with great accuracy.

The above formulæ may be written in the form :—

$$\text{Log}_{10} J = K_1 + K_2 \frac{1}{T}$$

where $K_1 = \text{Log}_{10}{}^{\lambda} C_1 - 5 \text{Log}_{10}{}^{\lambda}$ and $K_2 = C_2 \frac{\text{Log}_{10} e}{\lambda}$

This shows a linear relation between $\text{Log}_{10} J$ and $\frac{1}{T}$ and hence if the temperatures corresponding to two intensities be known the results may be plotted in the form of a straight line connecting T and J.

In certain optical pyrometers these theoretical considerations are made use of in practice. These instruments consist of a telescope fitted with a side branch in which a standard lamp is placed; light from the lamp is focussed upon a piece of transparent glass inclined at an angle of 45 degrees to the axis of the telescope from whence it is reflected to the eye-piece. To render the light monochromatic a piece of red glass is interposed between the lamp and the mirror. The telescope is sighted on a hot substance, rays from which pass through a piece of red glass and thence through two wedges of darkened glass, which diminish the intensity to a greater or less degree according to the thickness of absorbent glass interposed, which can be varied by sliding the wedges nearer or further apart. After passing through the wedges the light proceeds through the inclined mirror to the eye-piece. Consequently the appearance presented to the eye is that of a field illuminated one-half by the standard lamp and the other by the hot source. The adjustment consists in sliding the wedges by a screw movement until both portions of the field are equally illuminated. A temperature scale is provided on the moving piece which actuates the wedges, and it is derived by Wein's equation for the thickness of the wedges interposed when equality is obtained. calibration is effected by noting the thickness of the wedges corresponding to two known temperatures, from which a straight line connecting thickness with the reciprocal of the absolute temperature may be drawn and a table formed giving values of T in terms of the thickness of the wedges. The calibration may be extended indefinitely, the accuracy of the readings depending upon the truth of Wein's law. This makes a very convenient instrument for occasional readings of high temperatures, combining simplicity with portability.

There are many other pyrometers of this type in general use, including Wanners, The Cambridge Optical, and Holborn Kurlbaum, and of those which employ the matching of colours method, the best known are Lovibonds, Mesure and Nouels, and there are others still which work on the colour extinction method, such as the Pyromike.

Great care is needed in the use of all these pyrometers, and skilled workers are needed to take readings as the matching of tints, &c., demands a high degree of judgment. Very careful attention must be paid to the standard lamps and also, as the readings are black body readings, it is necessary that the same precautions should be observed as to focussing, &c., as in the total radiation pyrometers previously mentioned.

FUSION PYROMETERS.

This type of pyrometer depends on the fact that certain solids may be obtained which have progressive melting points, and if a number of these be placed in a furnace and are observed whilst in the furnace, some may be seen to have been unaffected, and others to have undergone fusion to a more or less extent. The temperature of the furnace is then known to be higher than melting point of the last solid melted, and lower than that of the first which has remained intact. The accuracy of the temperature determination depends of course on the interval between the successive melting points of the materials used. This method was foreshadowed by Wedgwood for use in the pottery kilns but in his case no attempt was made to measure temperatures *qua* such but only comparative results were needed.

In 1886 Segar in Berlin produced a series of silicates having progressive melting points, and by varying the composition he produced materials having melting points varying from 1,890°C. to 590°C., the interval between successive compositions being from 20 to 30°C. These materials were made up into triangular pyramids 5 cms. high with a triangular base of side 1·5 cms. When a test is being conducted pyramids are selected having melting points near to the required temperature. These are inserted in the furnace standing on a slab of refractory material and are watched through a sighting hole, the temperature of the furnace being estimated from observation of the cones. All the cones are stamped with a distinguishing number on the base so that they can be recognised and their melting points may be taken from the table supplied.

These cones are of great use when it is required to raise the temperature of the furnace to a definite amount, and then to remove the work or cool the furnace. But without a large expenditure of cones they are not suitable for use in a furnace which is required to be kept at a constant temperature.

Another form of these pyrometers are the "Sentinel" Pyrometers produced by Brearley of Sheffield. These consist of cylinders about 1 inch long by $\frac{3}{4}$ inch in diameter made of salts on definite melting points which collapse entirely on reaching their melting points. These cones may be found invaluable in the hands of untrained workmen, and as an instance of their use may be given the case of the heat treatment of shells, where it is found by experience that they will harden satisfactorily between two limits of temperature. In this case one Sentinel of the higher melting point may be issued to the furnace man who has orders on no account to let his furnace rise to such a height as to melt the upper Sentinel; whereas one Sentinel of the lower limit melting is placed inside each shell and this has to be seen to melt before the shell is removed from the furnace. In this way it is ensured that each shell is heated sufficiently high without overheating.