

(Paper No. 2630.)

“On the Measurement of High Temperatures.”

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THE importance of studying the varied metallurgical problems connected with the composition and structure of metals and their alloys, is becoming daily more evident; and, as this Institution has devoted attention to the consideration of metallurgical questions, it is hoped that a review of the present state of knowledge respecting the measurement of high temperatures may prove useful.

HISTORICAL.

The Author has elsewhere pointed out¹ that, notwithstanding the importance attached by early experimenters to the action of heat on metals, they had but little definite information respecting the relative degrees of intensity of heat; and their views were not inadequately expressed in the eighth century by Geber, who stated that great difficulties arose in conducting operations with the aid of heat, because heat cannot be measured, “*sed quoniam non est res ignis, quæ mensuari possit.*”² The name of Josiah Wedgwood is always associated with the early attempts to provide a practical method of pyrometry; but, although he wrote a thousand years after Geber, he seems to have merely changed the language of the latter, “heat cannot be measured,” into a lament that there were no trustworthy instruments for effecting the measurement of “the higher degrees of heat, from a red heat up to the strongest that vessels made of clay can support.”³ He therefore devised a pyrometer, which depended on the contraction that clay experiences when strongly

¹ Lecture at the Royal Institution. “Nature,” vol. 45, 1892, p. 534.

² From the edition of his “Summa Perfectionis Magisterii,” published in Venice, 1542, p. 28.

³ Phil. Trans. Royal Soc., vol. lxxii. 1782, p. 305.

heated. It is not necessary to give a history of pyrometry in this place; the Author would merely point out that Wedgwood demonstrated the necessity for the accurate measurement of high temperatures, and that, from his time, the invention of more or less suitable instruments has proceeded rapidly.

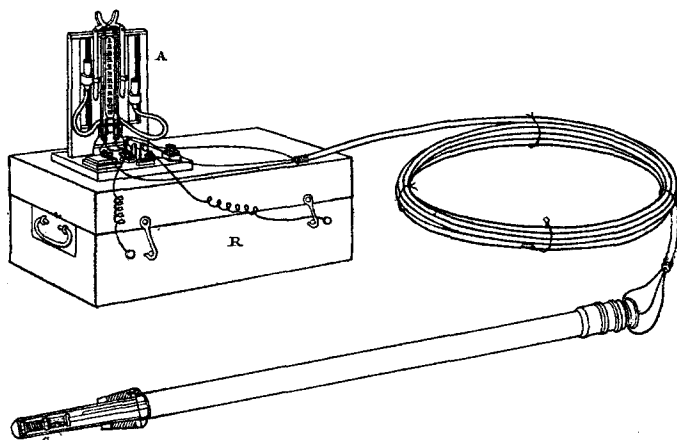
In the long interval between the work of Wedgwood and that of the late Sir William Siemens, such pyrometric appliances as were actually in industrial use depended mainly on what is known as the "method of mixtures,"—that is, upon the employment of a body, the specific heat of which was known, to transfer or carry heat from a furnace, or source of heat, to a measured volume of water, the rise in temperature of which was indicated by an ordinary thermometer. Pyrometers depending on the expansion of metallic strips or rods are also employed; but they may all be set aside with the general statement that, although they are useful in affording rough approximate measurements, they are useless for accurate pyrometry. It may be well to add that a noteworthy advance in thermometry has recently been made in Professor Ramsay's laboratory at University College, by Messrs. Baly and Chorley, who employ the fluid alloy of sodium and potassium, instead of the mercury of the ordinary thermometer; and, as temperatures of 600° Centigrade may thus be measured by thermometers of hard glass, further details of their experiments will be looked for with much interest.

MODERN WORK.

A new era in the measurement of heat began with the work of Sir William Siemens. He showed that electrical resistance might be used practically in pyrometry. *Fig. 1* gives a general view of his apparatus, and its nature is explained by the accompanying diagram, *Fig. 2*. A divided current passes from the battery B to a platinum wire C (coiled round a clay cylinder), and to a resistance-coil R. At the ordinary temperature, the resistance of the platinum coil is balanced by the standard resistance R, and an equal current will flow through each. If, however, the platinum coil C be heated, its resistance will be increased, and this increase of resistance can be measured in various ways. Siemens adopted for use in works, a small voltmeter, shown at A, *Fig. 1*; the current sent through the platinum coil *c* was of sufficient strength to decompose acidulated water,

and, the difference in the amount of water decomposed by that

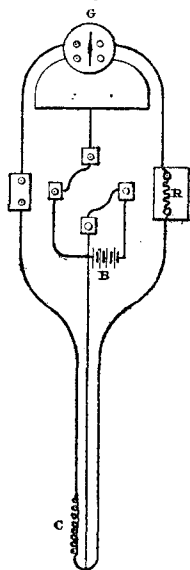
Fig. 1.



portion of the current which passed through the heated coil,

as compared with that decomposed by the current transmitted through the standard resistance at R, *Fig. 2*, gave, on reference to a Table, the temperature to be determined. For many years this electrical-resistance pyrometer was the only appliance, believed to be trustworthy, which could be placed in the hands of artificers. Its usefulness was widely recognized, and a Committee of the British Association was appointed to report upon it. The result of the inquiry¹ rather tended to shake confidence in the instrument, as it was shown that it was liable to changes of zero. Mr. H. L. Callendar² has, however, done much to prove that, with certain precautions, the method may be rendered very trustworthy. He winds the platinum wire on a plate of mica, excludes reducing gases, as the Committee suggested, by enclosing the coil in a tube of doubly-glazed porcelain, and uses a zero method of measuring the currents with the galvanometer.

Fig. 2.



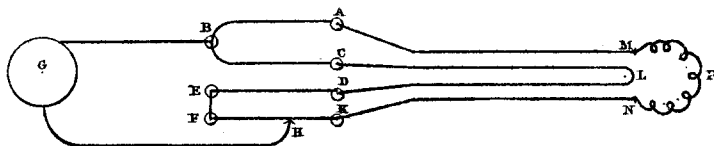
¹ British Association Report, 1874, p. 242.

² Phil. Trans. Royal Soc., vol. clxxviii. 1887, p. 161.

Fig. 3 represents, somewhat diagrammatically, the arrangement of the apparatus.¹

AB, BC are equal resistances, forming the arms of the balance. The battery is connected at A and C, and one terminal of the galvanometer G at B. DE represents a set of resistance coils, which, together with the resistances AB and BC, may be supplied by an ordinary box of coils of the "post-office" pattern. FK represents a straight bridge-wire, with a divided scale attached. The other terminal of the galvanometer is connected to the contact-piece H, which slides along this wire. The leads AM, KN, from the pyrometer coil P, are connected to A and K; and the compensating leads CL, LD, the resistance of which is equal to AM, KN, are connected to C and D. These four leads may be

Fig. 3.



of any convenient length; they are symmetrically arranged, so that corresponding parts are always at the same temperature. When the balance is found by inserting suitable resistances in the arm DE, and sliding the contact-piece H, it is plain that, since the resistances AB, BC, are equal, the resistance of the pyrometer and its leads, together with that of the length HK of the bridge-wire, will be equal to the remaining portion FH of the bridge-wire, together with the coils DE, and the compensation CLD. Thus, the changes of the resistance of the pyrometer-leads AM, KN, are compensated by the equal changes in the leads CL, LD, and the resistance of the pyrometer-coil itself is directly given by the sum of the coils DE, and the reading of the bridge-wire. The resistance of a centimetre of the bridge-wire FK is made to correspond to such an increase of the resistance of the pyrometer coil P, as is produced by a rise of 1° C. The contact key H slides along this wire, and the galvanometer can easily be made sensitive to one-hundredth of a centimetre of this bridge-wire; so that one-tenth of a centimetre, which corresponds to one-tenth of a

¹ Phil. Magazine, vol. xxxii. 1891, p. 104, and vol. xxxiii. 1892, p. 220.

degree, can, of course, be measured with certainty. The Author has worked for several days at the Royal Mint with Mr. Callendar, and is satisfied that, at temperatures exceeding that of bright redness, the comparative readings are accurate to one-tenth of a degree. This would have been considered impossible a few years ago, and the statement will, perhaps, be received with some incredulity. Later on, evidence will be examined which leads to the belief that, in the measurement of a "white-heat," degrees of value similar to those of the ordinary mercurial thermometer are still employed.

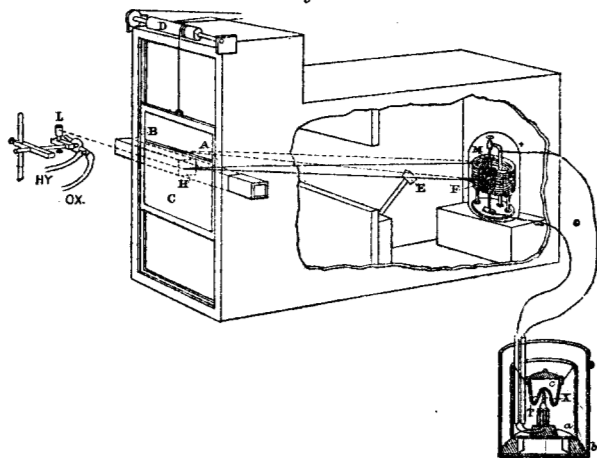
Measuring the increased resistance of a heated conductor is not the only way in which electricity has been made serviceable in the measurement of high temperatures. It has long been known that if a junction of two metals be heated, the electrical equilibrium of the system is disturbed, and the measurement of the difference of potential produced affords a means of estimating the temperature of the junction. The use of such thermo-junctions appears to have been suggested by A. C. Becquerel in 1826, and adopted by Pouillet ten years later. Unfortunately, the metals composing the thermo-junctions were badly chosen, and their use was consequently greatly retarded until, within the last few years, Professor H. Le Chatelier, of the École des Mines, Paris, advocated the use of platinum, in conjunction with platinum alloyed with 10 per cent. of rhodium. The Author first adopted this couple in 1889, and has since constantly used it, in conjunction with a photographic recorder, devised for the purposes of an investigation which was entrusted to him by the Institution of Mechanical Engineers. In its latest form, the instrument consists of two wires, one of the metal, and the other of the alloy mentioned above, simply twisted at their ends or soldered with gold, and connected with a dead-beat galvanometer of about 200 ohms resistance. The Deprez and D'Arsonval form of galvanometer, particularly the latest type of this instrument, is admirably adapted for use with this thermo-couple.

The arrangement, which is shown in *Fig. 4*, consists of a galvanometer of the Deprez and D'Arsonval type enclosed in a large camera; a fixed mirror *F* is placed below the movable mirror *M* of the galvanometer, so that the light from the lime cylinder *L*, reflected in the mirror *H*, passes to both mirrors, *F* and *M*, and is reflected in the direction of a fine horizontal slit *A B*; behind which a sensitized photographic plate *C* is drawn vertically past the slit, by means of gearing *D* driven by clockwork. The ray from the fixed mirror is interrupted periodically by the vane *E*,

and a beaded datum-line is given, which enables any irregularity in the advance of the plate to be detected.

The amount of divergence, from its datum-line, of the spot of light reflected by the movable mirror at any given moment, bears a relation (which can readily be found by calibration) to the temperature to which the thermo-junction X is heated; and the variations of temperature are denoted by a curve which is the resultant of the upward movement of the plate and the horizontal movement of the spot of light. A crucible *c* which may be filled with molten metal, is provided with a tubulure T for the insertion of the thermo-junction. The crucible is suspended by wires in a double jacket of tin plate, *a*, *b*.

Fig. 4.



The Author is satisfied that this thermo-junction can afford trustworthy results, accurate to 1° , at temperatures of over $1,000^{\circ}$ Centigrade. One important feature of the appliance is the minuteness of the space occupied by the thermo-junction, which may be suitably protected, and inserted into the midst of a very small mass of metal. The pyrometer is calibrated by exposing the thermo-junction to certain known temperatures, such as the solidifying points of salts or metals. There is no difficulty in recognizing the melting or the solidifying points; for, as the mass passes from the solid to the fluid state, the temperature remains constant for a brief period, the duration of which depends on the amount of material operated upon, and its latent heat of fusion; the result being that the spot of light from

the galvanometer will be arrested and the position on the scale, at which it stops, marks the temperature to be determined.

The electromotive-force produced by heating the thermo-junction to any given temperature, is measured by the movement of the spot of light on the scale, and, as has been above indicated, the scale is calibrated by heating the thermo-junction in contact with substances of known melting points.

The following list gives a sufficient number of such fixed points, which have been established by concurrent evidence of various kinds :—

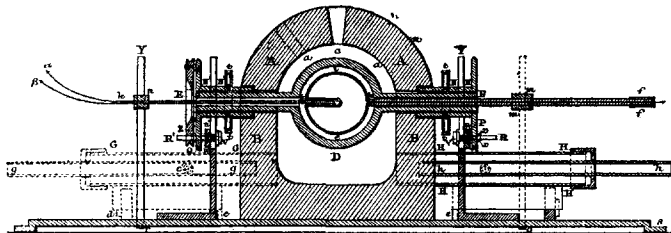
100° Centigrade	.	.	Boiling point of water.
326°	"	.	Melting point of lead.
358°	"	.	Boiling point of mercury.
415°	"	.	Melting point of zinc.
448°	"	.	Boiling point of sulphur.
625°	"	.	Melting point of aluminium.
665°	"	.	Boiling point of selenium.
945°	"	.	Melting point of silver.
1,015°	"	.	" " potassium sulphate.
1,045°	"	.	" " gold.
1,054°	"	.	" " copper.
1,500°	"	.	" " palladium.
1,775°	"	.	" " platinum.

They rest mainly, however, on determinations made with the air-thermometer. This valuable appliance need not be here described. It will be sufficient to state that its principle is the same as that on which the ordinary thermometer depends; the mercury being replaced by a gas, the expansion of which can be measured, and the glass bulb by a globe of porcelain.

The question naturally arises, how far may the indications afforded by the air-thermometer be trusted? Are the degrees indicated by it, at a white heat, comparable with the degrees of the ordinary thermometer? The Author believes that there is no reason to expect exceptional deviations from Boyle's law at the high temperatures of ordinary furnaces; and, further, the evidence as to temperature indicated by the air-thermometer does not rest upon the expansion of a single gas; as the porcelain bulb may be filled with nitrogen, oxygen, or carbonic anhydride. The question as to the degree of confidence which may be reposed in the numerical values of high temperatures is, however, so important, that the Author would refer to the following experiment of Carl Barus, who has devoted years of patient work to pyrometric investigations. *Fig. 5* shows

the arrangement adopted by him for comparing directly the air-thermometer with the thermo-junction.¹ The latter is inserted in a tubulure extending to the centre of the bulb *e*; and the disposition of the various parts of the apparatus is as follows. The walls of a cylindrical furnace *B B* are covered with a hemispherical dome *A A*. The furnace is heated by gas, introduced through the burners *G G*, *H H*; compressed air entering by the inner tubes *g g* and *h h*. The inlets for the gas are shown at *cc'*. The furnace can be heated to a high temperature with ease; but in order to equalize the heat, Barus employs an internal globular "muffle," *E C D F*. It consists of two hemispheres of fire-clay, provided with lateral tubes, which pass through the walls of the furnace. The two hemispheres are held together by the iron collars *N N*, *N' N'*. The outer edges of these collars *P P'* are

Fig. 5.



flanged, and fit into the grooves of two friction rollers, *Q Q'*, of which *RR R'* are the respective axes. There are adjusting screws at *V V'*, *uu', tt'*. The muffle is rotated by a belt pulley screwed on to the flange *P'*. The air thermometer is shown in position, *ffkie*, supported by the clamp *mm*. A similar clamp *nn* on the opposite side of the furnace, supports the thermo-junction *kk*, the wires of which are shown at *a β*. It will be observed that the thermo-junction passes directly into the re-entering tubulure of the porcelain bulb; but the wires must not touch the walls of the tubulure. The capacity of the bulb *e* is about 300 cc. The muffle is turned at the rate of about fifty revolutions per minute; and this speed, which is probably needlessly high, ensures uniformity in the temperature of the furnace.

It will be evident that the arrangements briefly described above enable the indications of the air-thermometer and the thermo-

¹ Bulletin United States Geological Survey, No. 54, Washington, 1889.

junction to be compared, and full details of the experiments will be found in a monograph by Barus. It will be found¹ that, if the results of the experiments be plotted with the electromotive-force of the thermo-junction (in micro-volts) as abscissæ, and the temperatures, indicated by the air-thermometer, as ordinates, the several observations coincide very nearly with a straight line; and singularly valuable information is thus afforded as to the trustworthy character of the respective methods. The general conclusion would appear to be,—that the thermo-junction, the use of which is very simple, may replace the air-thermometer, which, as arranged for accurate work, involves the employment of cumbersome apparatus and much tedious calculation; and is, in fact, about the last piece of apparatus that should be offered to engineers, with a view to the measurement of temperatures in the ordinary course of work.

An air-thermometer in a form adapted for industrial use has, however, been devised by Professor Wiborgh, of Stockholm,² who measures the pressure exerted by the expansion of a known volume of air, when forced into a porcelain bulb raised to the temperature which it is required to determine. Another form has recently been patented by Mr. H. L. Callendar;³ who has so modified the differential air-thermometer as to enable the degrees of temperature to be read directly on a graduated tube.

In conducting researches, the thermo-junction possesses, in the Author's opinion, many advantages; but, unfortunately, its use involves appliances which are not sufficiently simple to be entrusted to ordinary workmen; and, as Professor Le Chatelier has pointed out, the use of the thermo-electric pyrometer is only possible in works where the engineer has a taste for scientific investigation, and devotes himself personally to it. In this country such cases are not rare, and the Author would only cite, as an instance, the Clarence Works; where Sir Lowthian Bell has established a system of electrical pyrometry in connection with the hot-blast mains; each of which may, in turn, be placed in pyrometric communication with a central office.

A less complicated but still trustworthy instrument of moderate accuracy was much needed; and Professor Le Chatelier has recently supplied one. The eye of the workman again becomes the pyrometer, but it is supplemented by an instrument which

¹ *Loc. cit.*, p. 226.

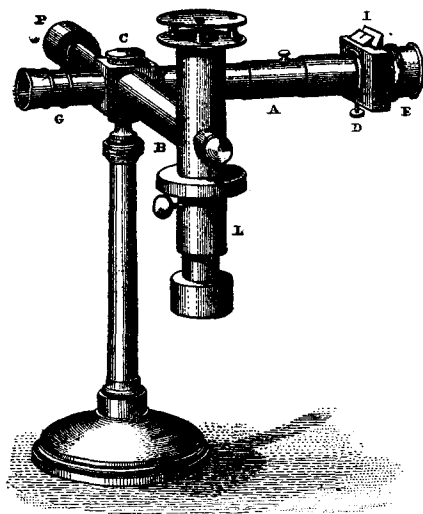
² Journal of the Iron and Steel Institute, 1888, vol. ii. p. 110.

³ Proceedings of the Royal Society, 1892, vol. i. p. 247.

enables him to record the intensity of the radiations emitted by a glowing body; so that the old method of judging temperature by the appearance of the mass is rendered comparatively accurate, and the familiar indications of "redness," "bright redness," and "whiteness," are subjected to direct measurement. Optical pyrometry is not new; but its history, which would include references to the honoured names of Pouillet, Ed. Becquerel, Crova, and Violle, is far too complex to be dealt with in this Paper.

Mr. Crova¹ actually employed his spectro-pyrometer for indus-

Fig. 6.



trial work, and measured the temperature of certain furnaces at the Creusot Works.

Le Chatelier's² new photometric instrument is shown in *Figs. 6, 6a*, and in its construction he has introduced the photometer of Mr. Cornu. The Author is indebted either to Le Chatelier's recently published Papers, or to descriptions which he has furnished, for the details respecting the instrument which will now be described. The light, from a standard flame, or lamp L, burning anylie

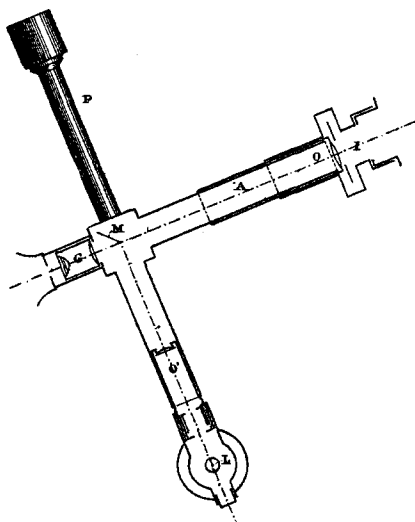
¹ Comptes Rendus, vol. lxxxvii. 1878, pp. 322 and 979; *ibid.* vol. xc. 1880, p. 252; *ibid.* vol. xcii. 1881, pp. 36 and 707; *ibid.* vol. cxiv. 1892, p. 941.

² Comptes Rendus, vol. cxiv. 1892, p. 214; *l'Industrie Électrique*, No. 7, 1892, p. 147, where the formulas given in this Paper will be found.

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acetate, is reflected to the eye of the observer by the mirror M, while the light from the incandescent body also passes to his eye through a red glass in the eye-piece G; this renders the radiations nearly monochromatic. There is an adjustable orifice at O, by which the amount of light admitted from the luminous body can be regulated. In order that intensities, which may often vary from 1 to 1,000,000, may be compared, absorbent glasses are employed; and these glasses are superposed at O' and E, in greater or less number, as may be necessary. P is a counterpoise, to equalize the weight of the other parts of the appliance. The luminous object, the temperature of which has to be deter-

Fig. 6a.



mined, may be focussed by sliding the tube A'; and in order to measure the intensity of its radiations with this instrument, the procedure is as follows:—The position of the mirror M must be regulated by three screws at C, Fig. 6, so that the luminous image of the lamp, and that of the object to be measured, are brought into juxtaposition, being divided by the edge of the mirror.

The photometer depends upon the adjustment, to the same brightness, of two images; one being that of the flame of a standard lamp, and the other that of the object whose temperature is to be determined. The adjustment is made by means of a diaphragm formed of two plates, each with V-shaped notches opposite to one

another. The two plates can be moved past one another by turning a milled head, D, and in this way a square aperture of variable size is formed; which, being placed in front of the object-glass O of the telescope, controls the amount of light admitted from the luminous object.

A divided scale I is attached to one half of the diaphragm, and a pointer to the other, and this gives directly a linear measurement n of the aperture.

Let n' be a measurement, when the image of an object of unit brightness (a candle-flame for instance) is matched to that of the standard lamp; and n the measurement, when another object is matched in place of the candle. Since the eye-piece has a red glass within it, only red rays pass to the eye for measurement, and the intensity I, of these red rays emitted by the second object, as compared with those from the candle, will be given by the equation

$$I = \left(\frac{n'}{n}\right)^2.$$

But, if the two objects are not at equal distances from the instrument, the intensity will be apparently less for the more distant one, in the ratio $\left(\frac{f}{f'}\right)^2$, where f and f' are the focal lengths (given on the tube A) of the two objects; hence—

$$I = \left(\frac{n'}{n}\right) \times \left(\frac{f}{f'}\right)^2.$$

As has been already stated, the great differences of intensity which have to be measured, occasionally render it necessary to absorb some of the rays from the object or from the standard lamp, as the case may be. This is done by inserting neutral-tinted glasses in suitable holders, either at E or F. Let N' be the linear measurement of the aperture, when the luminous object, shaded by a neutral tinted glass, is matched with the standard lamp; and let N be a similar measurement when the same object is unshaded.

Then the coefficient of absorption of the glass, K , will be given by the equation

$$K = \left(\frac{N'}{N}\right)^2;$$

and, when p thicknesses of the neutral glass are before the object, whilst the standard lamp is left unshaded,

$$I = \left(\frac{n'}{n}\right)^2 \left(\frac{f}{f'}\right)^2 \left(\frac{I}{K}\right)^p.$$

On the other hand, for measuring very low temperatures, when the standard lamp is shaded by p thicknesses of glass, and there are no glasses before the diaphragm, the formula becomes

$$I = \left(\frac{n}{n}\right)^2 \left(\frac{f}{f'}\right)^2 K^p,$$

the index p being required because each glass cuts off a fraction of the light received by it.

Experiments indicate that the change in intensity of the red rays from a body of temperature T , is approximately given by the equation

$$I = 10^{6.7} T^{-\frac{3210}{T}},$$

where T is reckoned from absolute zero, so that $T = (t^\circ\text{C} + 273)$, t being the actual reading of the thermometer. This formula has been used to calculate the numbers given in the following Table—

Temperature. Centigrade.	Intensity of Red Rays.
600°	0.00008
800°	0.0046
1,000°	0.078
1,200°	0.64
1,400°	3.35
1,600°	12.9
1,800°	39.0
2,000°	93.0

the unit intensity being that of the axial zone of the flame of a standard candle.

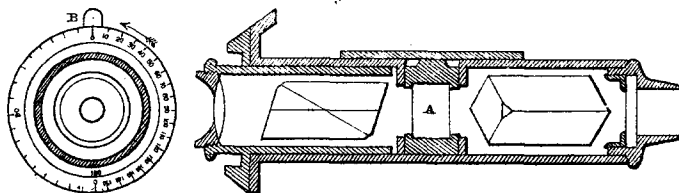
In one instrument, where n' (the reading obtained with a candle flame as a luminous object) was 5.2, and $\frac{1}{K}$ had the value $\frac{1}{2.5}$, the following figures were obtained by Professor Le Chatelier :—

Temperature. Centigrade.	One Glass before Stan- dard Lamp.	No Neutral Glasses.	One Glass before Diaphragm.	Two Glasses before Diaphragm.
700°	39.5			
800°	15.2			
900°	7.4			
1,000°	3.8	19.2		
1,100°	..	10.8		
1,200°	..	6.7		
1,300°	..	4.2	21.2	
1,400°	..	2.7	13.8	
1,500°	..	..	10.1	
1,600°	..	..	7.4	
1,700°	..	..	5.6	
1,800°	..	..	4.3	21.5
1,900°	..	..	..	17.0
2,000°	..	..	..	13.8

But, inasmuch as the emissive power of different bodies for red rays is not the same under like conditions as to temperature, it will be doubtless preferable to calibrate the instrument directly by comparing it with a little mass of platinum, or of oxide of iron, which can be maintained at known temperatures as measured by a thermo-couple.

There is another optical instrument, the pyrometer devised by Messrs. Nouel and Mesuré,¹ and used by the Author for some years in the laboratory of the Royal School of Mines. It consists of a quartz plate *A* (*Fig. 7*) placed between two Nicol prisms; an arrangement that renders it possible to suppress, at will, the radiations of any particular part of the spectrum, by simply rotating one of the Nicol prisms. If a hot body be observed through the instrument, and the prism be rotated by means of the

Fig. 7.



divided head *B*, the red colour of the body will be seen to change to yellow, then to green, and finally to blue. The angle of rotation necessary to extinguish the red colour varies with the temperature, and serves as a measure of it; but the difficulty of remembering the precise tint by which the instrument was calibrated, prevents a high degree of accuracy from being attained in its use.

The importance of being able to measure high temperatures will now be considered with special reference to the work of the engineer. It is evident that the advantages of measuring and controlling the temperatures at which industrial operations are conducted, are more apparent on the metallurgical side of engineering practice than on any other; but, apart from metallurgy, there are many problems in the solution of which pyrometry is of much service. The unaided eye, even of a trained and skilful workman, dealing with a special set of conditions with which he is familiar, is, probably, a far less trustworthy guide than it is often supposed to be; for, in estimating the temperature of a furnace, or that of a glowing mass of metal, much will depend upon the relative

¹ Minutes of Proceedings Inst. C.E., vol. lii. p. 419.

brightness of the illumination of the surrounding space. The Author has had considerable experience in estimating the somewhat high temperatures of the "muffles," or little ovens used in the assay of gold and silver; but, on actually measuring, by means of the optical pyrometer, the temperature of two muffles in different positions in the same laboratory, he was surprised to find that they differed by more than 50° , although both appeared to be of nearly the same temperature.

Some measurements, made by the optical pyrometer, of temperatures employed in conducting industrial operations will now be given:—

GOLD MELTING, ROYAL MINT.

	Centigrade.
Temperature of standard alloy, pouring into moulds . .	$1,180^{\circ}$
" " " (on a previous occasion, by thermo-couple) . . .	$1,147^{\circ}$
Annealing blanks for coinage, temperature of chamber .	890°

SILVER MELTING, ROYAL MINT.

Temperature of standard alloy, pouring into mould . .	980°
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OPEN-HEARTH FURNACE, WOOLWICH ARSENAL.

Hot gases in interior of melting chamber, about . . .	$1,806^{\circ}$
Temperature of steel, 0·3 per cent. carbon:	
Pouring into ladle	$1,700^{\circ}$
Pouring into moulds	$1,700^{\circ}$
Pouring into moulds at end	$1,650^{\circ}$

10-TON OPEN-HEARTH FURNACE, WOOLWICH ARSENAL.

Temperature of steel, 0·3 per cent. carbon, pouring into ladle	$1,645^{\circ}$
Temperature of steel, 0·3 per cent. carbon, pouring into large mould	$1,580^{\circ}$
Re-heating furnace, Woolwich Arsenal, temperature of interior	930°
Cupola furnace, temperature of No. 2, cast-iron pouring into ladle	$1,600^{\circ}$

It is, of course, useless to attempt to deduce the temperature of a heated space, such as the interior of a re-heating furnace, from the radiations of an object which has been newly placed in it, and has therefore not had time to become thoroughly heated. Some experience in the use of the instrument is necessary, but the Author does not find that there is much divergence between his observations and the results obtained by his assistant, Mr. H. C. Jenkins, Assoc. M. Inst. C.E.

Professor Le Chatelier ¹ had previously measured the temperature attained in conducting some familiar operations; and, as the results obtained by him are, in the case of certain industries, entirely at variance with the estimations which have hitherto been made, it may be of interest to quote a few of them:—

BESSEMER CONVERTER (6 TONS CAPACITY).

	Centigrade.
Pouring of the slag	1,580°
" " steel into ladle	1,640°
" " " into mould	1,580°
Re-heating furnace	1,200°
Ingot under the hammer	1,080°

SIEMENS-MARTIN OPEN-HEARTH FURNACE.

Gas—

Temperature of gas on leaving generator	720°
" " " entering regenerative chambers	400°
" " " leaving " " "	1,200°
" " air " " " " "	1,000°
" " products of combustion approaching the chimney	300°

Metal (about $\frac{3}{10}$ per cent. carbon)—

Temperature at end of fusion of pig-iron		1,420°
" " "fining" of the steel		1,500°
" " pouring of the steel into the ladle {beginning		1,580°
	{end . . .	1,490°
" " " " " into the mould.		1,520°

REGENERATIVE FURNACE FOR CRUCIBLE STEEL.

Temperature in the spaces between the crucibles . . . 1,600°

BLAST FURNACE, SMELTING GREY PIG.

Opening in front of the "tuyere"		1,930°
Tapping the pig	{beginning	1,400°
	{end . . .	1,570°

SIEMENS FURNACE, USED FOR MELTING GLASS.

Furnace	1,400°
Melted glass	1,310°
Annealing the bottles	585°
Furnace for hard porcelain, end of the "baking"	1,370°
Hoffmann kiln (brick-burning)	1,100°
Temperature of incandescent electric lamps from	1,800° to 2,100°

The accurate measurement of high temperatures is increasing in interest, in view of the rapid development of the study of

¹ Comptes rendus, vol. cxiv. 1892, p. 470.

chemical dynamics.¹ It is now recognized that the industrial chemist, as well as the engineer, has to deal with the influence of mass. Many chemical processes are reciprocating, so that the original product may be obtained from the product of the reaction. The result of such opposed processes is a state of chemical equilibrium, in which the original and the newly-formed substances are present in definite quantities; and remain the same so long as the conditions, more especially those of temperature and pressure, do not undergo further change. In conducting many operations, temperature and pressure are reciprocal factors; thus, in the manufacture of oxygen on an industrial scale, from air, by the intervention of oxide of barium, the latter is heated to a constant temperature of 700° Centigrade, and the air is admitted to the heated mass under a pressure of $1\frac{1}{2}$ atmosphere; while the oxygen, then absorbed, is again evolved, if the containing vessel be rendered partially vacuum. It is evident that, at a certain critical temperature and pressure, the slightest variation of either will destroy the equilibrium in such a system, and induce chemical change. Hence the importance of being able to measure with accuracy a bright red heat. Now, as Professor Le Chatelier has already pointed out, in the production of chlorine by the Deacon process, or in the baking of porcelain, a variation of temperature of only 20° is attended with complete failure of the operation. There is, however, one other case of more direct interest to the engineer, in relation to steel. It involves the consideration of the possibility of the occurrence, at high temperatures, of molecular changes in steel, which profoundly modify its mechanical properties; and although it is difficult to describe briefly the nature of this change, the following statement may be sufficient.

When a mass of steel is cooled from a very bright red heat, say from 1,200° Centigrade to the ordinary temperature of the atmosphere, at least three critical points, each attended by an evolution of heat, may be detected by the pyrometric methods already indicated; and their position may be determined very precisely by the aid of the autographic method already described and illustrated. The development of the theory of the importance of these critical points is mainly due to Osmond,² who has fixed the

¹ Roberts-Austen, Presidential Address, Chemical Section of the British Association. Cardiff, 1891.

² See Report by the Author to the Alloys Research Committee of the Institution of Mechanical Engineers. Proceedings, No. 5, 1891, p. 543, and 'Nature,' vol. xli. 1889, pp. 11, 32, where references are given to Osmond's Papers.

normal temperatures at which they occur during the slow cooling of a mass of steel; and these are approximately as given in the following Table, in which the notation of Chernoff and of Osmond has been retained.

	Centigrade.
A ₁ Is caused by the change of "hardening carbon" into carbide of iron (Fe ₃ C), and occurs when the temperature of the cooling mass has fallen to about	650°
A ₂ Coincides with the appearance of magnetic properties in the iron. It is due to an allotropic transformation in the iron, and occurs between	700° & 740°
A ₃ Is also due to an allotropic modification in the iron, and normally occurs at	855°

The Author believes that these changes are of great importance in modifying the structure, and consequently the mechanical properties, of steel; and he is fortunate in sharing this opinion with Dr. Anderson, the Director-General of Ordnance Factories, who is instituting, at Woolwich Arsenal, some interesting experiments bearing on the question. The initial temperature of the mass, and its rate of cooling, are not without influence on the temperatures at which these critical points occur. For instance, in hardening large pieces of steel, such as the "A" tubes of guns, it may happen that, when the mass is plunged into the oil bath, a portion of the metal may be at a temperature below that at which the molecular transformations occur. In large masses of steel, the bath may exert a "hardening" action on the hot interior of the mass of steel, and none at all on the cooler surface. It is, moreover, only necessary for the temperature of different parts of the mass to vary within a narrow range, in order that the bath may exert different influences on adjacent parts of the steel. This is a matter of great importance, and Mr. Barba of the Creusot Works began its study in 1880, but abandoned the attempt for want of sufficiently exact and practical methods of measuring high temperatures. The Author attacked the problem last year, and published the results of the only experiment which has, as yet, been made. For the purpose of conducting it, Dr. Anderson caused an ingot of steel to be prepared, 8 inches high and 4 inches in diameter. It contained carbon 0·799, silicon 0·084, manganese 0·412. A Le Chatelier thermo-junction was placed in a hole drilled to the centre of the mass, and another thermo-junction was fixed in a hole drilled near the surface. The mass was heated to bright redness, the external junction indicating 1,100° Centigrade, each thermo-junction being in turn switched into connection with the recording apparatus, *Fig. 4*; and dotted curves repre-

senting the cooling of the exterior and at the interior of the mass were thus obtained. The cooling was effected by plunging the mass into water. The effect of rapid cooling on the surface was, of course, to contract it and to compress the mass; the pressure being very marked in the zone of the ingot in which the external thermo-junction was inserted. The result appeared to be a lowering of the critical point (which should have occurred at about 660° Centigrade) to a little over 400° Centigrade.

It would therefore appear that the great problems of chemical equilibrium are applicable to the relations between the constituents of the complex material, steel; and that the pressure exerted on the molecules of a metallic mass must be measured, as well as its temperature, in investigating the molecular grouping of metals, upon which their mechanical properties depend.

In conclusion, it may be well to indicate briefly some other directions in which the measurement of high temperatures may be useful. The spent gases from boiler-furnaces are often hotter than 400° , and their temperature should, in many cases, be accurately known. In researches on heat-engines, complex problems arise demanding a knowledge of temperatures of about 500° . Foundry practice presents numerous cases, as, for instance, casting guns by the Rodman system; in conducting which it is most important, as Mr. H. B. Howe, of Boston, has pointed out, to be able to measure and control the rate of cooling of the core of the gun, as compared with its outside. By this means, it is possible to avoid setting up prejudicial stresses, and to promote the development of useful ones in castings of all kinds. Mr. George Addy has appealed to the importance of pyrometry, in connection with experiments on armour-piercing projectiles; and it will be evident that the use of projectiles and explosives is a branch of engineering fertile in problems, the solution of which must, in a great measure, be based on pyrometry.

The gradual introduction of new alloys is changing the methods of investigation which must precede and govern the use of materials in construction. It may be thought that work of the kind indicated in this Paper is not sufficiently practical to deserve the attention of the engineer. If fears of this kind should arise, the Author would recall the eloquent words recently addressed by a Member of Council¹ of this Institution to such doubters; who, he says, "can never have been placed in positions of responsibility, where the safety of ships, the lives of their passengers and crews,

¹ The Director-General of Ordnance Factories.

the efficiency of armaments, and their own financial position were in question; they can never have looked at masses of steel, with the view of deciding whether they were fitted for the purpose for which they had been produced; nor can they ever have felt the helplessness, and the want of reasonably secure guidance, which it is still the lot of the responsible judge to experience." The guidance for which Dr. Anderson appeals can only be afforded by employing to the fullest extent, the methods, as well as the results, of physical and metallurgical research.

The Paper is illustrated by Diagrams, from which the *Figs.* in the text have been prepared.