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On the Heat Dissipated by a Platinum Surface at High Temperatures

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XII. *On the Heat Dissipated by a Platinum Surface at High Temperatures.*

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[Plates 18–23.]

From the beginning of the century, and more especially of late years, an almost uninterrupted series of papers have appeared on the above subject. Unfortunately few of the authors have reduced their measurements to absolute units, thus rendering comparison of the results obtained very difficult.

The first part of this paper is to some degree an extension to higher temperatures and pressures of the work so ably done by Dr. Bottomley,* whilst the names of Langley, Paschen,† Weber,‡ and many others will occur to anyone glancing through the second and third parts.

With regard to temperature measurements, the present work is mainly founded on the researches of Callendar and Griffiths,§ which have been amply confirmed by the later investigations of Heycock and Neville.‖

Full references to the above papers are given here once for all, as we shall have continually occasion to refer to one or other of them.

On the Apparatus Employed.

The preliminary experiments soon showed that to obtain reliable results a very thick wire must be used for the double purpose of radiator and thermometer, even if it were at the cost of a slight loss of sensitiveness, the reasons being the following :—

* 'Phil. Trans.,' A, vol. 178, 1887, p. 429, and 'Phil. Trans.,' A, vol. 184, 1893, p. 593.

† 'Wied. Ann.,' vol. 49, p. 50, 1893; vol. 58, p. 455, 1896, and vol. 60, p. 663, 1897.

‡ 'Physical Review,' vol. 2, p. 112; 'Berichte der Preussischen Akademie,' 1888, p. 933, &c.

§ 'Phil. Trans.,' A, vol. 182, p. 119, 1891.

‖ 'Journ. of the Chem. Soc.,' vol. 67, p. 160, 1895; same vol., p. 1024; 'Phil. Trans.,' A, vol. 189, p. 25, 1897. On this subject see also C. M. Clarke, 'The Electrician,' vol. 38, pp. 175, 241, 372, and J. D. H. Dickson, 'Phil. Mag.,' December, 1897, p. 445.

25.10.98.

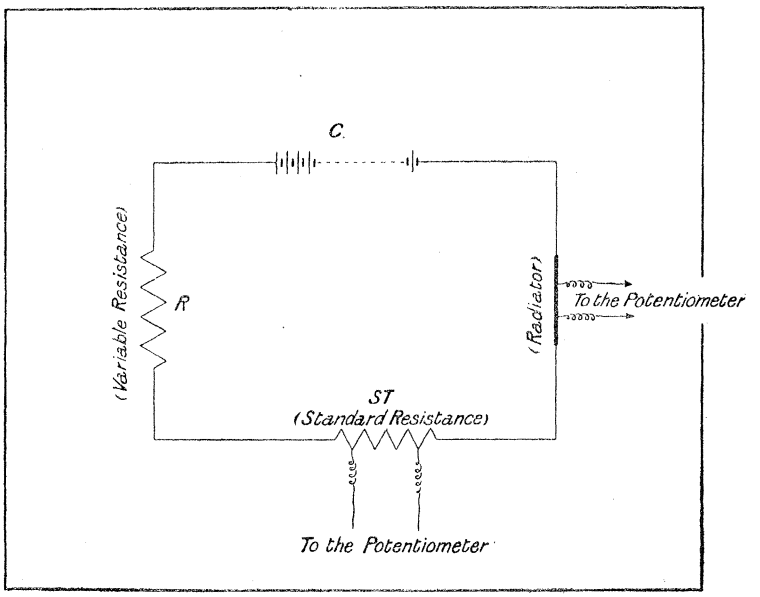
1. A thin wire maintained at any temperature above 1200° is subject to a rapid increase of resistance.

2. It is impossible to obtain consistent results with a thin wire at atmospheric pressure, owing to the constant fluctuation in temperature due to convection currents.

3. As pointed out by Professors AYRTON and KILGOUR, with fine wires the emissivity, referred to unit of surface, depends largely on the diameter, but the rate of change decreases rapidly as the diameter increases.

The diameter of the wire used was ·112 centim., or nearly 1 sq. millim. in cross-section. The resistance of the thermometers was about ·01 ohm at 0° C., or about one five-hundredth of the resistance usually employed.

Fig. 1.



The electrical connections can be briefly described as follows:—At C, in fig. 1, is a set of forty cells, which by the aid of a mercury commutator can be placed in any desired combination, either series or parallel. This commutator was used to make the first rough adjustment of the current. R is a variable resistance consisting of thirteen German silver tubes, which are kept at a constant temperature by a water circulation. The resistance is designed to carry up to 150 amperes. By two sliding contacts, one of which serves as a fine adjustment, the current can be regulated to within ·01 of its value. The current through the radiator is measured by aid of the standard resistance ST, the exact value of which, according to the Reichsanstalt certificate, is ·0099965 ohm at 16·55 C., its temperature coefficient being ·0003 per cent. A small motor was used to maintain a circulation of oil round the wires of this resistance, the oil being in its turn cooled by a water circulation. By this means the temperature of the standard was prevented from rising above 25° C.

All electrical measurements have been referred to this standard and to a Clarke's cell (N 5217 A), its value being taken as 1·4331 volts at 16° C.

Both the current through, and the electromotive force at the terminals of the platinum wire, were measured on a Wolff potentiometer. In none of the coils did the error exceed ·02 per cent. The temperature coefficient was less than ·001 per cent.

The radiators used were calibrated at frequent intervals, a slight increase in absolute resistance and in temperature coefficient being noticeable.

One of these sets of readings is given below :—

Radiator R_2.

R_{100} = resistance at 100° C. . . . . ·012252

R_0 = resistance at 0° C. . . . . ·009907

$c = \frac{R_{100} - R_0}{100}$ . . . . . ·00002345

$\delta = 1{\cdot}304.$

The value of δ is deduced from the resistance of the wire in sulphur vapour by CALLENDAR'S formula,

$$t - pt = \delta \left(\left[\frac{t}{100} \right]^2 - \left[\frac{t}{100} \right] \right),$$

where t is the temperature in degrees Centigrade,

pt = temperature in platinum degrees = $\frac{R - R_0}{c}$, and

δ = a constant.

The platinum thermometer has rarely been used to determine temperatures above 1100°. It is therefore necessary to obtain some confirmation of the above formula for temperatures up to 1500°. For this the melting point of palladium was chosen, and the value given by VIOLLE,* 1500° C., taken as correct.

A length of about 3 millims. of palladium wire ·01 centim. in diameter was held against the platinum radiator. The temperature being gradually increased, the palladium soon became viscous and adhered to the platinum, finally fusing at a very sharply-defined temperature.

To this method there is an obvious objection. With each fusion there is a certain weight (·0004 gram, or ·03 per cent. in this case) of palladium added to the platinum. This would produce an appreciable change in the electrical constants. To obviate this difficulty it is necessary to fuse the palladium on a part of the platinum wire, not between the potential leads, but sufficiently near them to be substantially at the same temperature.

* 'Comptes Rendus,' vol. 87, p. 983, 1878.

The melting point of palladium calculated in this way from the formulæ of CALLENDAR and GRIFFITHS was for the thermometer R_2 1489°, as against 1500° as determined by VIOLLE.

A second confirmation of the temperature determinations will be found in the fact that in all the curves given below, the calculated temperatures agree with those determined directly by the fusion of platinum or palladium.

Finally, it may be well to state here that although every precaution was taken to ensure the accuracy of the results, the absolute resistance of the wires used was too small for me to lay claim to as great a degree of precision as that obtained by HEYCOCK and NEVILLE in their valuable researches on the melting point of metals. Up to about 500° I believe the results given to be correct to a fraction of a degree, but above 1200° it is difficult to prove that they are absolutely exact.

In Table I. will be found a determination of the volume specific resistance of platinum and palladium. The values obtained for platinum show that the temperatures above 1500° cannot be calculated by the ordinary equations; these, for instance, in the case of R_2 would give for the melting point of platinum a temperature more than 100° too low.

Part I.—On the Emissivity of a Bright Platinum Surface in Air and other Gases.

Throughout the experiments, the results of which are given in Tables II. to XIII., a cylindrical glass enclosure, 5·8 centims. in diameter and 24 centims. in height, was used. The straight platinum wire, which served at the same time as radiator and thermometer, was placed in the axis of the cylinder. A platinum wire, 2 millims. in diameter, bent into the form of a "J" and fused at its lower extremity on to the thermometer, formed the return lead. This wire, as well as the potential leads, was kept well to the side of the enclosure. The enclosure was always used with its axis vertical. This arrangement forms the simplest geometrical disposition of the surfaces of the radiator and enclosure that can be used with the method adopted, as for obvious reasons a sphere enclosed in a sphere is out of the question.

A sufficient length was left between the point of contact of the lower potential lead and the terminal of the radiating wire, for the wire to acquire a constant temperature.

As pointed out by Dr. J. T. BOTTOMLEY, the low thermal conductivity of glass is a very serious objection to its use as an enclosure in experiments on emissivity, it being possible for the inner surface to rise to a temperature very appreciably above that of the water circulation. Owing to this fact, it was not thought advisable to take any observations with the radiator at much less than 100° above the enclosure. At temperatures higher than this a slight error in the estimation of the temperature of the enclosure would not alter the results.

A large number of experiments were made, but only the most typical results have been recorded here. The observations are given in the tables according to the order in which they were taken. In Table IIA will be found an illustration of the way in which all the results were worked out.

The curves relating to air, hydrogen, carbon dioxide, oxygen, and steam are given in figs. 2, 3, 4, and 5. The pressure in centimetres of mercury is indicated on each curve. Observations for each of the first three gases are given at three distinct pressures, for steam and oxygen the emissivity is only determined at a pressure of 76 and 228 centims. respectively.

The degree of purity of the hydrogen used was 97 per cent., the remaining 3 per cent. being, in all probability, air. The carbon dioxide, which was prepared from calcium carbonate, contained less than 1 per cent. of impurities.

During the course of each experiment the exact height of the barometer and the temperature of the room, the standard resistance, and the potentiometer, were recorded. The temperature of the enclosure was also read at short intervals of time on a thermometer divided in tenths of a degree. These factors have too little effect on the main point at issue for each of the readings to be recorded here.

In the course of the preliminary experiments it was found that the emissivity, as far as these results are concerned, is practically independent of the condition of the glass surface (whether perfectly clean and freshly polished or covered with a thin layer of lamp-black), and of the exact position of the radiator in the enclosure.

The emissivity does not seem to bear any simple relation to the specific gravity of the gas. In hydrogen, and to a lesser degree both in carbon dioxide and in oxygen, the emissivity is greater than in air.

In fig. 2 the rise in emissivity caused by saturating the air with moisture will be seen. The difference in emissivity is nearly constant throughout the entire range of temperature, averaging ·0001 therm. per second per square centimetre of surface, per degree above the enclosure. This is all the more remarkable as the average temperature of the air, and therefore the quantity of water vapour present, naturally increases with the temperature of the radiating wire.

In fig. 6 some curves will be found giving the relation between the temperature of the wire and the mean temperature of the gases in the enclosure. These curves were obtained by using the enclosure itself as a rough form of air thermometer, the measurements being made at atmospheric pressure. The three gases are here in the same order as when classed with regard to the experiments on emissivity. For all the gases included in this study, the rise of emissivity due to any given increase of pressure is not proportional to the initial value of the emissivity, but is more nearly constant at all temperatures.

For facility of reference some parts of the hydrogen curves given both in fig. 2 and fig. 3 (Plate 18), and the curve representing the emissivity in air at three atmospheres, will be found again in fig. 4 (Plate 19).

The emissivity in steam at atmospheric pressure is given in fig. 5. The slope of the curve is much sharper than for any of the gases previously studied. This fact, as we shall see from the results given below, cannot be entirely accounted for by the higher temperature of the enclosure.

I hope shortly to undertake a research on the emissivity of platinum in gases at a much higher pressure. For the present the results are too incomplete to allow any general theory to be formulated.

The values obtained for the emissivity are to some extent dependent on experimental conditions, such as the diameter of the radiating wire, its position in space (whether horizontal or vertical), the dimensions of the enclosure, its absolute temperature, and the material of which it is made. For the results to be of any general application, it is necessary to form an idea of the extent to which they are affected by these divers factors.

Curve I. in fig. 7 (Plate 20) is taken with the radiating wire in the square gun-metal box described in Part III. of this work. For Curves II. and III. the wire was placed in the axis of an iron cylinder 2·6 centims. in diameter, 27·5 centims. long. In all three cases the wire was horizontal.

Curve IV. has already been given in fig. 2; it refers, as do all the results given above, to a wire ·112 centim. in diameter placed vertically in the axis of a glass cylinder 5·8 centims. in diameter.

The difference between the Curves I. and IV. is mainly due to the change of position. When the wire is vertical, the part on which the observations are taken is surrounded by a layer of gas which rises from below after being heated to substantially the same temperature as the wire itself. When the wire is horizontal, the hot gas rising from it is replaced by a fresh supply at nearly the same temperature as the enclosure. The variation between Curves I. and II. is about 10 per cent. It is a difference of this order that we may expect when the shape, size, and material of the enclosure are radically changed. In cases, however, where the ratio of the surface of the radiator to the surface of the enclosure is not kept very small, the total loss of heat depends very largely on the dimensions of the enclosure.

Curve III. is taken in the same iron cylinder as used for Curve II. In this case the iron was kept at a high temperature by surrounding it with a jacket containing boiling sulphur. The temperature of the enclosure, as measured by the platinum wire subsequently used as the radiator, was somewhat high. This temperature, namely, 455° C., or ten degrees above the usual boiling point of sulphur, can easily be accounted for by the direct heating effect of the flame, for the prevention of which no precautions were taken.

The slope of the curve of emissivity obtained at this temperature is considerably steeper than that relating to experiments with the enclosure at a lower temperature.

The above-mentioned curves, which are given in fig. 7, all refer to the emissivity in dry air at atmospheric pressure.

The usual definition of the emissivity of a body, and the one I have adhered to throughout, may be expressed as follows :—The emissivity is numerically equal to the number of gramme-degrees, or therms, dissipated per second, per square centimetre of surface, per degree above the enclosure. The "true emissivity" at any temperature, t, might be defined as the slope at the temperature t of the tangent to the curve representing the total heat dissipated plotted in terms of the temperature. In other words, if h is the loss of heat per square centimetre per second at any temperature, t, the "true emissivity" at this temperature is dh/dt.

The Curves II. and III. (fig. 7), if plotted in terms of the true emissivity, would almost coincide, showing that in this case, at any rate, the value obtained depends to a very limited extent on the temperature of the enclosure.

A comparison of Curves I. and V. will show the effect of using a wire ·6 millim. instead of 1·12 millims. in diameter.

Finally, in fig. 7, the points marked AA′ refer to a platinum wire, 2·005 millims. in diameter, that is to say, nearly twice the diameter used in all previous experiments. The wire was fused in the gun-metal enclosure, and the results must therefore be compared with the point B, obtained under identical conditions, but with a wire 1·12 millims. in diameter.

It will be seen that the decrease in emissivity due to the use of the larger wire is, at this temperature, less than 7 per cent.

The emissivity at the points of fusion of palladium and platinum were deduced from the readings of instruments of the Weston type, which were afterwards calibrated by aid of the potentiometer. The wire was raised to within about 100° or 200° of the melting point. The current was then increased by equal amounts of $\frac{1}{2}$ or $\frac{1}{4}$ per cent., and current and electromotive force readings were taken at each successive rise. The current was noted at the instant the wire fused, the corresponding electromotive force being easily found by extrapolating the last few readings. Over 100 amperes were needed to fuse the 2 millims. wire, and for accurate results to be obtained it was necessary for this large current to remain constant to within a tenth of a per cent. This experiment, as many of those previously recorded, was only rendered possible by the exceptional facilities available at the Davy-Faraday Laboratory.

A large proportion of the work done on the subject of emissivity refers to the cooling of comparatively large bodies. This method was used by Dulong and Petit, J. C. Nichol,* McFarlane,† C. F. Brush,‡ Dr. J. T. Bottomley, and many others. These results cannot serve as points of comparison. Added to the effect of the absolute size of the bodies used, the question of the relative surfaces of the enclosure and radiator comes here into play. Whenever the ratio of these two surfaces is not very

* 'Proc. Roy. Soc.,' Edin., 1869, vol. 7, p. 206.
† 'Proc. Roy. Soc.,' 1872, vol. 15, p. 90.
‡ 'Phil. Mag.,' vol. 45, p. 31, Jan., 1898.

small, its absolute value has a considerable influence on the rate of cooling of the enclosed body.

SCHLEIERMACHER's* results only apply to radiation in a high vacuum, but BOTTOMLEY, in his researches on the same subject, incidentally gives one value at atmospheric pressure; this is for a temperature of 408° C. It works out at nearly one and a-half times the emissivity for the same temperature as shown in Curve I., fig. 7.

From the resistance given in Dr. BOTTOMLEY's paper, it is probable that the wire used was about ·3 millim. in diameter. If this be the case, the difference is what might have been predicted from the results obtained by Professors AYRTON and KILGOUR.†

The formulæ given by them for the connection between the emissivity of the wire and its diameter are

$$\text{At } 200^\circ \text{ C. } e = \cdot00111 + \cdot014303d^{-1}.$$
$$\text{At } 300^\circ \text{ C. } e = \cdot001135 + \cdot016084d^{-1}.$$

The wires were heated in a horizontal position and the diameters measured in millimetres.

The diameter of the wire used was 44 millims. Inserting this value for d in the above formulæ gives for the value of the emissivity at 200° and 300° C. ·00144 and ·00150 C.G.S. units. The values given in Curve I., fig. 7, are ·00107 and ·00121. The largest wires used in establishing the above formulæ were 14 millims. It is therefore not surprising if, after extrapolating for a wire over three times this diameter, the calculated and experimental values differ considerably. This divergence is also in some degree accounted for by the fact that the enclosures used in the two cases were of an entirely different shape and size.

In a paper recently published, Mr. C. F. BRUSH gives a number of observations "on the transmission of heat by gases," at temperatures of from 0° to 15° C. Unfortunately it is impossible to reduce these to absolute units. The relative value of the emissivity in air and in hydrogen is much the same as that which may be deduced at some hundred degrees higher from fig. 2. My measurements show that the emissivity in carbon dioxide is greater than in air at high temperatures, converging to the same value at 150° C. At about 10° C., according to Mr. C. F BRUSH, the relative value of the emissivity in these two gases is reversed.

Many formulæ have been given, principally with regard to radiation in vacuo; but I am aware of none that will apply at atmospheric pressure and high temperatures.

Until more is known as to the physical constants of gases at temperatures ranging from the melting point of silver to the melting point of platinum, it is doubtful whether any general law can be obtained.

* 'Wied. Ann.,' vol. 26, p. 287, 1885.

† 'Phil. Trans.,' A, vol. 183, p. 371, 1892.

Part II.—A Bolometric Study of the Law of Thermal Radiation.

The relative merits of the laws of Dulong and Petit, and Stefan, have formed the subject of a number of researches. It is sufficient to recall the experimental work of Schleiermacher* and Schnebeli,† which appeared in 1884, and the theoretical discussion of the subject by Ferrel‡ some five years later. In 1888 Professor Weber§ proposed a new expression connecting the thermal radiation with the absolute temperature of the radiator and the enclosure. This expression, as he showed, accounted satisfactorily for the greater part of the experimental results then available. It was with the hope that some additional data with regard to the total radiation at higher temperatures might help the elucidation of the problem that the present experiments were carried out.

Most of the apparatus employed has been already described in Part I. For the experiment we are now about to describe the radiating wire was placed in a metal enclosure kept at a constant temperature by a water circulation. A number of diaphragms, also provided with water circulations, shielded the bolometer from all external radiation.

The bolometer used was of a somewhat special construction. Many weeks were spent in preliminary experiments before the design of the instrument was finally fixed. It is with a desire to spare this loss of time to others that a somewhat full description of the bolometer is given here.‖

The instrument is symmetrical throughout, one side containing the active platinum film which is exposed to the radiation, the other side an exactly similar film forming the second arm of the bridge. For the platinum silver foil from which these films were made I am indebted to the kindness of Mr. J. S. Sellon, of Messrs. Johnson, Matthey and Co.

A thin sheet of platinum was welded to a thick sheet of silver, the two sheets, protected on each side by a copper plate, were then rolled together and a leaf was thus obtained, of sufficient thickness to be quite easily handled. This I cut on the dividing engine into the shape of a grid (as shown in fig. 8, F). It was then placed in the holder (fig. 8, A), and the silver dissolved in dilute nitric acid. The film of platinum left was found to have a thickness of ·00011 centim., or about twice the wave-length of sodium light. The active surface has the appearance of a grating, consisting of fifteen bars, 3 millims. wide, with a space of 1 millim. between each bar. The span from the upper to the lower edge of the carrier is 56 millims. The

* 'Wied. Ann.,' vol. 26, p. 287.

† 'Wied. Ann.,' vol. 22, p. 430, 1884.

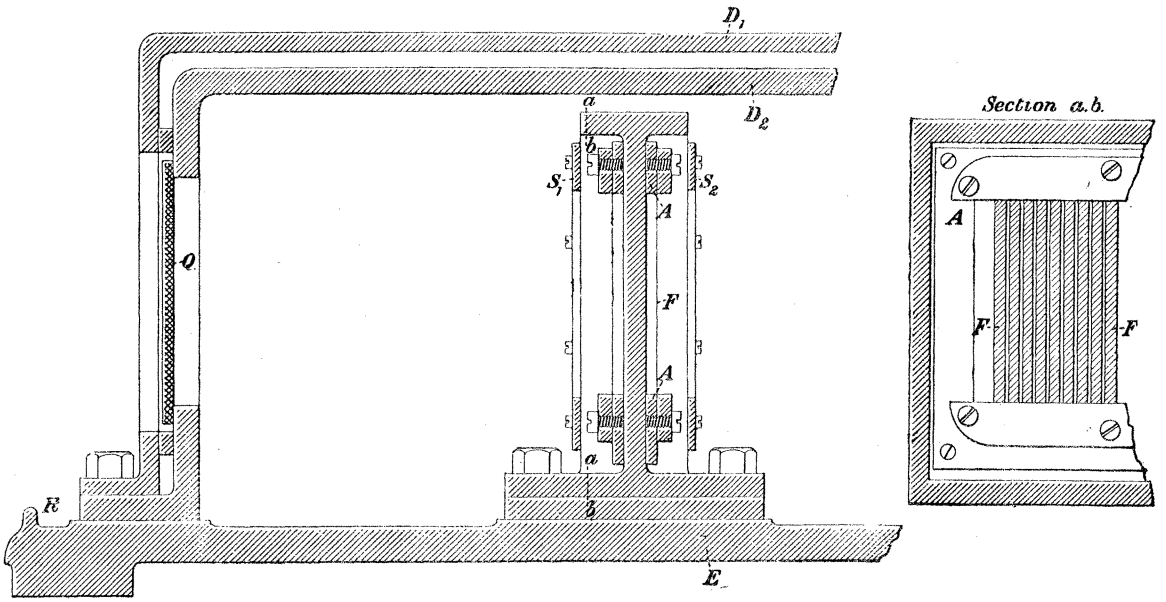
‡ 'American Journal of Science,' vol. 38, p. 3, 1889.

§ 'Berichte der Preussischen Akademie,' 1888, p. 933.

‖ Those interested in this subject will do well to refer to an article by Lummer and Kurlbaum ('Wied. Ann.,' vol. 46, p. 204, 1892; or, 'The Electrician,' vol. 34, pp. 168, 192, 1894).

practical difficulties in the construction of so thin a film are considerable, and in designing a new instrument it would be advisable either to reduce the size of the film or to increase its thickness. The very thin platinum, obtained in the way we have just described, though capable of withstanding a large amount of vibration, cannot resist the slightest mechanical strain, a touch with a single hair being sufficient to break it. Great care is needed in the manipulation of the film from the moment the silver is dissolved off it until it is screwed up in position in the instrument. During this time it has to receive an electrolytically deposited coating of platinum black, be washed several times, and carefully dried. When once in position in the instrument there is, however, comparatively little chance of an accident.

Fig. 8.



The desiderata of a good bolometer may be enumerated as follows:—

1. Great sensitiveness.
2. Constancy of zero.
3. Rapidity of action.

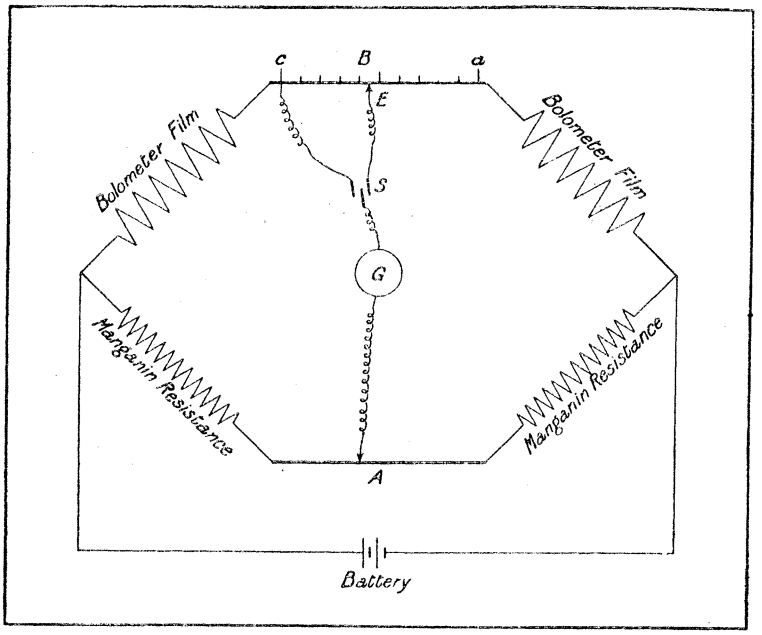
The first and third conditions are fulfilled, thanks to the extreme thinness of the platinum and to its high temperature coefficient. The sensitiveness was found to be increased by coating the films on one side only with platinum black, and by placing behind them a nickel mirror. With regard to rapidity of action it was found in the course of some subsequent experiments that the platinum rises in half a second to over 90 per cent. of its maximum temperature.

The second condition, namely the constancy of the zero point, is the most difficult to fulfil. It has already been pointed out that the four arms of the bridge must be in pairs as nearly as possible identical, not only with regard to resistance, but also with regard to shape, size, position, and temperature coefficient. But these pre-

cautions are not sufficient. To avoid thermo-electric disturbances it is necessary to keep all the working parts of the bolometer at the same temperature. To attain this object the entire instrument was made of metal. The insulation of the films at their upper and lower extremities where they are secured to the carriers is provided for by very thin strips of mica. The working parts of the bolometer were protected by two massive metal covers, D_1 and D_2, fig. 8, fitting one over the other, and between which room is left for a water circulation.

The variations due to convection currents formed one of the most serious difficulties. Following the suggestion of Professor DEWAR, the instrument was constructed to allow of the films being used in a vacuum. As shown in fig. 8, the double cover is bolted down on to the bedplate, E. The joint is kept covered with oil which is poured into the rim, R.

Fig. 9.



A vacuum can only be used for experiments in which the absorption of the quartz plate, Q, is not a serious objection. The screens, S_1 and S_2, are intended to regulate the path of the convection currents when the instrument is used under atmospheric pressure; they also screen the edges of the film from direct radiation. The two other arms of the bridge are made of manganin wire, the coils being placed in an earthenware vessel filled with oil.

The resistance of each of these two coils is 20 ohms, and the resistance of each of the bolometer films 23 ohms. The connections of the instrument are diagrammatically shown in fig. 9. The bar, A, is of German silver, and serves to adjust the zero of the galvanometer. The bar, B, between the potential contacts, c and d, is divided into 1000 parts of equal resistance, the length between the potential contacts is 80 centims., the resistance ·007730. This bar serves to calibrate the galvano-

meter. By the switch, S, one terminal of the galvanometer can be thrown over from the zero point of the bar to the sliding contact, E, which has been previously set at any desired division.

If n be the number of divisions at which the sliding contact is set, $n \times 2 \times \cdot 00000773$ is the change in resistance of the bolometer film,* which would produce an equal galvanometer deflection. Where the total radiation received is large, a zero method can be used, and the change in resistance measured directly by the position of the slider, E, on the bar, B.

As regards sensitiveness, the deflection obtained with a candle at 1 metre from the instrument was 360 millims. The total electromotive force on the terminals of the bolometer was 2 volts, the time period of the galvanometer 10 seconds, and distance of the scale 1·3 metres. Each film before being mounted was tested at a pressure of 30 volts, so that any electromotive force up to 60 volts could be used without danger, but no advantage would be gained by increasing the pressure above 10 or 15 volts. The main object in view has not been to obtain excessive sensitiveness, but to construct an instrument which would give thoroughly reliable results. In almost all cases a much smaller degree of sensitiveness than that given above has been found amply sufficient.

The law of thermal radiation may be studied by two entirely distinct methods. We can either measure the heat lost by the radiating surface when in a nearly perfect vacuum, or the heat received by the sensitive surface of some type of radiometer.

The determinations by the first method will exceed the true value by some quantity, $m.\mathrm{R}$, representing the heat carried away by any gas or vapour remaining in the enclosure.

The numbers obtained by the second method will fall below the actual value of the radiation by some quantity $n.\mathrm{R}$, where $n.\mathrm{R}$ represents the part of the radiation not absorbed by the irradiated surface.

If R be, at any given temperature, the true value of the radiation, and O_1 and O_2 the observed values obtained by the two methods described above, we have:

$$\text{I.} \quad \mathrm{O}_1 = c_1 (\mathrm{R} + m.\mathrm{R}),$$

$$\text{II.} \quad \mathrm{O}_2 = c_2 (\mathrm{R} - n\mathrm{R}),$$

where c_1 and c_2 are constants depending merely on the experimental conditions and on system of units chosen.

In Equation I., m represents the ratio between the heat dissipated by convection and conduction and the heat radiated. Now it is well known that this ratio decreases as the temperature increases. The slope of the curve of radiation obtained by this method will therefore always be somewhat less steep than the true curve of radiation.

* The change in the resistance of the bolometer film produced by the radiation being thus known, it is an easy matter to express the heat received in gramme-degrees. In the present case, however, as we are only dealing with relative values, little advantage would be gained by the use of absolute units.

Considering now Equation II., we see that here also the second term decreases as the temperature rises; for it has been shown that whereas a surface coated with platinum-black or lamp-black almost totally absorbs all radiation of short wave-length, it reflects a comparatively large proportion of the infra-red rays. The curve obtained by any form of radiometer will therefore be steeper than that representing the actual relation between total radiation and temperature.

The foregoing conclusions may be summed up as follows :—

The rate of change of the total radiation with temperature will be too small when measured by the heat lost by the radiating body, whereas it will be too large when measured by the heat gained by an irradiated surface coated with lamp-black or platinum-black.

Finally we may note that, as both m and n decrease at higher temperatures, the accuracy of both methods increases as the temperature rises.

Let us now see to what extent the actual experimental work verifies the conclusions we have just arrived at.

In fig. 10 (Plate 21) the values obtained by the first method are represented by the results of Dr. J. T. Bottomley and of Schleiermacher, whereas the second method was used by F. Paschen and by myself.

To facilitate the comparison of the slopes of the curves, all the results are reduced to the same arbitrary value at a temperature of 800° C.

We see that Curve No. II., obtained by Bottomley, lies between the Curves No. I. and III. obtained respectively by Schleiermacher and by Paschen, or precisely in what is for theoretical reasons the most probable position of the true curve of radiation.

I have recently made a series of determinations by aid of the bolometer described above; the results within the limits of the probable experimental errors fall on this same curve.

It seems very probable that Curve II. represents the actual law of thermal radiation between 400° and 800° C., but even were this not so, we might safely admit that the true curve must fall somewhere between Curves I. and III., fig. 10. All expressions therefore giving values outside these limits may be discarded without further study. The formulæ of Stefan, of Dulong and Petit, and of Rosetti, fail when tested by this criterion. Weber's formula, on the other hand, agrees closely with Curve II. from 400° to 800° C. At all higher temperatures the rate of change of radiation with temperature calculated by this formula, is certainly too great.

Taking the value of Weber's constant at 800° C. as unity and comparing the calculated results with Curve II., we obtain 1·01, ·96 and ·94 for the values of the constant for 700, 600 and 500 degrees centigrade, showing that the expression remains nearly correct over this range of temperature.

Table XVI. and fig. 11 give the results of a series of observations on the radiation from platinum at temperatures ranging from 500° C. to the point of fusion of the metal.

In Table XVII. a few results obtained from the readings of a thermopile, the surface of which was coated with lamp black, are recorded. These results, though much less accurate than those obtained by use of the bolometer, serve as a confirmation of the previous values and show that these values are not affected by the type of instrument used.

Part III.—On the Variation of the Intrinsic Brilliancy of Platinum with Temperature.

The flux of light emitted by one square centimetre of platinum at a fixed temperature has many times been proposed as a standard of light. By Violle* this temperature is defined as the point of solidification of the metal, whereas Lummer and Kurlbaum† advocate a lower temperature not far from the melting point of palladium. It was essentially as a preliminary to the study of these two standards that the present work was undertaken. The method employed for the temperature measurements was in every particular the same as used in the first part of this paper. The experiments were made with wires 1·12 millims. in diameter enclosed in a gun-metal box $8 \times 8{\cdot}5 \times 3$ centims., which could be fitted with diaphragms of any desired shape. The wire under observation was horizontal, the points of contact of the potential leads being a little more than one centimetre to the right and left of the edge of the diaphragm, the opening of which was 38 millims. in length. The walls of the gun-metal casting forming the enclosure were hollow, and a water circulation maintained the temperature at about 15° C.

As standards of comparison, incandescent lamps were used. These were first left burning for from fifty to one hundred hours to avoid the initial rapid change in candle-power and then compared with a number of standard candles; the usual corrections being in all cases applied where the candles burnt more or less than the prescribed forty grains of sperm in ten minutes. The candle-power of these lamps was finally established from the mean of some hundreds of photometric readings. While any one of these lamps was in use, the electromotive force at its terminals was kept constant by the aid of a potentiometer. No photometric reading during which the electromotive force had varied more than ·05 per cent. from its correct value, was recorded.

Where the lights differ largely in colour, as was the case in most of the observations recorded in the table, the measurements become influenced mainly by two physiological phenomena—

(1.) The relative value of two lights of different colour depends on the absolute illumination of the two surfaces used in comparing them.

* 'Comptes Rendus,' 1884, p. 1032, vol. 98.

† 'Elektrotechnische Zeitschrift,' 1894, p. 475.

(2.) LEPINAY and NICATI* have shown that the intensity of a light is not the same when measured by the distinctness with which the details of an object can be seen as when measured by the apparent brightness of a surface. The form of photometer used is sufficient indication that it is the latter method which has been adopted for the experiments recorded here.

In 1879 VIOLLE† published a research on much the same subject as is here dealt with. His results and mine though in substantial agreement as to the intrinsic brilliancy of platinum at its melting point, differ considerably at lower temperatures. In the paper alluded to no information is given as to the methods or instruments used, it is therefore impossible to suggest to what the divergence may be due. The author sums up his results by giving for the relation between the temperature, t, and the light emitted, I, the formula

$$\text{Log I} = 8{\cdot}244929 + 0{\cdot}011475t - 0{\cdot}00000297t^2.$$

This expression by a modification of the constants could doubtless be made to agree with the present results; but the formula given below, owing to its simplicity, will be found of more practical value.

If t denote the temperature in degrees centigrade, and b the intrinsic brilliancy of the surface in candle-power per square centimetre, the relation may be expressed as

$$(t - 400) = 889{\cdot}6\sqrt[6{\cdot}9]{b}.$$

The temperature calculated by this formula‡ will be found in column 3 of Table XVIII. The crosses on fig. 13 represent the intrinsic brilliancy as calculated. The circles show the values obtained experimentally.§ Where the formula is used over so wide a range of temperature the agreement for the lower values is but approximate; but this expression will be found to give very correct values of b when used for a limited interval above and below any temperature for which the constant has been determined.

Finally, before bringing this paper to a close, I desire to express my deep indebted-

* 'Annales de Chimie et de Physique,' 1883, vol. 30, p. 145.

† 'Comptes Rendus,' vol. 88, 1879, p. 171.

‡ When the platinum is observed in a dark room, the first grey light becomes visible at a temperature of 417° C. It is as the limiting temperature, so far as visible radiation is concerned, that 400° C. is used in this formula.

§ I have recently made a number of observations on the intrinsic brilliancy of the crater of the electric arc. As these results refer to a study at present far from complete, it will be sufficient to state here that the intrinsic brilliancy is about 11,000 candle-power per square centimetre. Inserting this value for b in the formula given above, we obtain 3830 as the temperature of the crater. This fact may be taken as a confirmation of the formula for temperatures above the melting point of platinum, though I do not think that it would be wise to attach much importance to a coincidence of this kind.

ness to Professors DEWAR and FLEMING, and to Dr. A. SCOTT, who throughout this work have most kindly helped me with their advice on the more difficult theoretical points, and with their long experience of all the details of experimental work.

NOTE ADDED 14TH SEPTEMBER, 1898.

It has been suggested that the standard resistance referred to on p. 502, owing to the large currents which were used, might in reality rise to a temperature much in excess of that indicated by the thermometer, and thus by the consequent change in resistance materially affect the accuracy of the observations. The following experiment was carried out to ascertain to what extent this actually took place.

A platinum resistance was constructed similar to the standard manganin resistance referred to above. This new resistance was calibrated as a platinum thermometer. It was then placed in the same oil bath as used for the manganin standard. An electric current of increasing intensity was passed through it, and after each successive increase of current the temperature of the oil was read on an ordinary mercury thermometer, and the temperature of the platinum strip was calculated from its resistance. The stirrer was, of course, kept in motion during the entire experiment.

The results, reduced so as to apply to the manganin standard, are given in the following table :—

Current through the standard.	Probable rise of the manganin strip above the temperature indicated by the mercury thermometer.
amperes.	° C.
18·6	0·3
39·6	1·4
57·0	3·1
74·3	4·9
102·0	9·3

This standard resistance was rarely used for currents above 50 amperes, and never for currents above 70 amperes. For larger currents it was replaced by a ·001 ohm resistance. However, taking an extreme case, and supposing 74·3 amperes to be passing (the temperature coefficient being ·0003 per cent.), it is clear that the rise of temperature would not involve an error of more than ·0015 per cent.

TABLE I.—On the Volume Specific Resistance of Platinum and Palladium at their Melting Points.

Platinum.			Palladium.		
Number of radiator.	Volume specific resistance.		Number of radiator.	Volume specific resistance.	
	C.G.S. units.			C.G.S. units.	
R_2	62,720	Mean volume specific resistance of platinum at its melting-point = 62,600 C.G.S. units.	R_{10}	53,960	Mean volume specific resistance of palladium at its melting-point = 54,700 C.G.S. units.
R_3	63,140		R_{11}	55,400	
R_7	61,760				
R_8	62,370				
R_9	62,830				

TABLE II.—Emissivity in Dry Air at Three Atmospheres Pressure (See fig. 2.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
50	·0008234	24th February, 1898. Temperature of the enclosure 9° C.	765	·002006	26th February, 1898. Temperature of the enclosure 10° C.
322	·001337		996	·002545	
800	·002082		1130	·002758	
1087	·002658		1370	·003520	

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE IIIA.—Emissivity in Dry Air at Atmospheric Pressure. (See fig. 2.)

2nd March, 1898.

Current, first reading.	Electro-motive force, first reading.	Current, second reading.	Electro-motive force, second reading.	Mean current.	Mean electro-motive force.	Resist-ance.	$\frac{R-R_0}{R_0=\cdot01006.}$	$\frac{R-R_0}{\cdot00002345}$	Tem-perature.	Energy dissipated in Watts.	t_r-t_e. Tempera-ture of the radiator above the enclosure.	$\frac{W}{t_r-t_e}$.	$\frac{W}{J\times S\,(t_r-t_e)}$ = emissivity
amperes.	volts.	amperes.	volts.	amperes.	volts.	ohms.		° pt.	° C.				
6·392	·07830	6·429	·07845	6·411	·078375	·01223	·00217	92·55	93	·5025	81	·006204	·0006640
9·125	·1280	9·130	·1280	9·1275	·1280	·01402	·00396	168·9	171	1·1685	159	·007348	·0007866
16·91	·3835	16·89	·3833	16·90	·3834	·02269	·01263	538·7	574	6·480	562	·01153	·001234
20·34	·5470	20·34	·5470	20·34	·5470	·02689	·01683	717·8	789	11·13	777	·01432	·001533
24·175	·7452	24·175	·7450	24·175	·7451	·03082	·02076	885·5	1003	18·01	991	·01817	·001945
28·75	·9910	28·73	·9915	28·74	·99125	·03449	·02443	1042	1219	28·49	1207	·02361	·002529

Temperature of the enclosure, 12° C.
" " standard resistance, 18·5° C.
" " Clarke's cell, 16° C.
Height of the barometer corrected to 0° C., 751·8 millims.
S = superficial area of wire between the potential terminals = 2·224 sq. centims.
t_r = temperature of radiator in degrees centigrade.
t_e = " of enclosure " "

Radiator, R_2,

$$pt = \frac{R - \cdot01006}{\cdot00002345},$$

$$t - pt = 1\cdot3035\left[\left(\frac{t}{100}\right)^2 - \frac{t}{100}\right],$$

where pt is the temperature in platinum degrees, and t the temperature in degrees centigrade.

TABLE IIIB.—Emissivity in Dry Air at Atmospheric Pressure. (See fig. 2.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.	3rd February, 1898. Temperature of the enclosure 20° C.	° C.	C.G.S. units.	3rd February, 1898. Temperature of the enclosure 20° C.
1281	·002717		528	·001141	
1172	·002378		387	·000992	
1044	·002031		293	·000878	
877	·001760				
700	·001380		Radiator. ° C.		
			R_3 1779	·004960	

TABLE IV.—Emissivity in Air at Atmospheric Pressure saturated with moisture. (See fig. 2.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.	3rd March, 1898. Temperature of the enclosure 11° C.	° C.	C.G.S. units.	28th February, 1898. Temperature of the enclosure 10° C.
1331	·002977		142	·000833	
1196	·002550		236	·000966	
1036	·002115		377	·001106	
888	·001800		534	·001290	
751	·001553				
533	·001257		Radiator. ° C.		
203	·000845		R_{10} 1500	·003820	
74	·000666		R_{11} 1500	·003945	
			R_4 1779	·005228	

TABLE V.—Emissivity in Dry Air at 1 centim. Pressure. (See fig. 2.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.	11th February, 1898. Temperature of the enclosure 13° C.	° C.	C.G.S. units.	22nd February, 1898. Temperature of the enclosure 9° C.
922	·001137		1291	·001145	
1002	·001365		715	·000870	
1137	·001590		268	·000490	
1244	·001995				

TABLE VI.—Emissivity in Dry Hydrogen at Three Atmospheres. (See fig. 3.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.	3rd March, 1898. Temperature of the enclosure, 10° C.	° C.	C.G.S. units.	2nd March, 1898. Temperature of the enclosure, 10° C.
119	·003336		971	·006720	
183	·003686		188	·003679	
271	·004029				
408	·004535				
770	·005916		141	·003499	8th March, 1898. Temperature of the enclosure, 9° C.
			680	·005721	
			1281	·008270	

TABLE VII.—Emissivity in Dry Hydrogen at Atmospheric Pressure. (See fig. 3.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
123	·002577	7th March, 1898. Temperature of the enclosure, 9° C.	1020	·005386	7th March, 1898. Temperature of the enclosure, 9° C.
222	·002970		1324	·006459	
291	·003209		1305	·006435	
384	·003509				
526	·003955				
692	·004385		Radiator. ° C.		
690	·004373		R_6 1779	·00942	
886	·004962		R_7 1779	·00940	

TABLE VIII.—Emissivity in Dry Hydrogen at 6 centims. Pressure. (See fig. 3.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units	
195	·002213	8th March, 1898. Temperature of the enclosure, 9° C.	1120	·004520	8th March, 1898. Temperature of the enclosure, 9° C.
487	·002853		427	·002668	
725	·003413				
741	·003350				
954	·003954		1265	·004988	7th March, 1898. Temperature of the enclosure, 9° C.
			288	·002345	

TABLE IX.—Emissivity in Dry Carbon Dioxide at Three Atmospheres Pressure. (See fig. 4.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
371	·001428	28th February, 1898. Temperature of the enclosure, 9° C.	821	·002322	1st March, 1898. Temperature of the enclosure, 9° C.
277	·001271		1020	·002808	
157	·001031		1160	·003230	
61	·000783		1269	·003594	
			1331	·004098	
554	·001776	1st March, 1898. Temperature of the enclosure, 9° C.			
685	·002028				

TABLE X.—Emissivity in Dry Carbon Dioxide at Atmospheric Pressure. (See fig. 4.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
1278	·002892	17th February, 1898. Temperature of the enclosure, 11° C.	1249	·002809	18th February, 1898. Temperature of the enclosure, 11° C.
1267	·002816		1361	·003197	
1167	·002541		1419	·003407	
1026	·002157				
762	·001582				
			90	·000655	28th February, 1898. Temperature of the enclosure, 9° C.
			241	·000888	
			483	·001155	

TABLE XI.—Emissivity in Dry Carbon Dioxide at 6 centims. Pressure. (See fig. 4.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
188	·000422	21st February, 1898. Temperature of the enclosure, 10° C.	1097	·001712	21st February, 1898. Temperature of the enclosure, 10° C.
312	·000530		1200	·001971	
988	·001447		1374	·002540	
708	·000975				
			1334	·002385	18th February, 1898. Temperature of the enclosure, 10° C.
			521	·000715	

TABLE XII.—Emissivity in Oxygen at Three Atmospheres. (See fig. 4.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
815	·002092	28th February, 1898. Temperature of the enclosure, 9° C.	1135	·002882	28th February, 1898. Temperature of the enclosure, 9° C.
413	·001429		1291	·003463	
723	·001914		61	·000848	

TABLE XIII.—Emissivity in Steam at Atmospheric Pressure. (See fig. 5.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
962	·002392	3rd March, 1898. Temperature of the enclosure, 107° C.	925	·002174	3rd March, 1898. Temperature of the enclosure, 107° C.
1293	·003489		754	·001714	
764	·001742		534	·001268	
1122	·002790				

TABLE XIV.—Emissivity in Air at Atmospheric Pressure. Wire horizontal in cylindrical iron enclosure. (See fig. 7, Curves II. and III.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
858	·00216	29th January, 1898. Temperature of the enclosure, 455° C.	61	·000676	29th January, 1898. Temperature of the enclosure, 22° C.
919	·00234		106	·000848	
1007	·00260		188	·000991	
1142	·00309		381	·001225	
629	·00155				
778	·00189				
912	·00239				

TABLE XV.—Emissivity in Air at Atmospheric Pressure. Gun-metal Enclosure. Radiating Wire Horizontal. Diameter of Wire · ıtim. (See fig. 7, Curve I.)

Temperature.	Emissivity.		Temp ıre.	Emissivity.	
° C.	C.G.S. units.		C.	C.G.S. units.	
64	·000814	Temperature of the enclosure 17° C.	771	·001952	Temperature of the enclosure 17° C.
89	·000899		785	·001972	
118	·000962		804	·002034	
133	·000976		861	·002147	
219	·001133		942	·002312	
276	·001159		945	·002344	
351	·001272		1016	·002532	
385	·001309		1115	·002832	
420	·001393		1150	·002915	
481	·001477		1171	·003018	
510	·001540		1274	·003387	
615	·001693		1371	·003754	

TABLE XVI.—Emissivity in Air at Atmospheric Pressure. Gun-metal Enclosure. Radiating Wire Horizontal. Diameter of Wire ·0600 centim. Radiator No. R_{24}. (See fig. 7, Curve V.)

Temperature.	Emissivity.		Temperature.	Emissivity.	
° C.	C.G.S. units.		° C.	C.G.S. units.	
1012	·002782	Temperature of the enclosure 16° C.	522	·001990	Temperature of the enclosure 16° C.
890	·002546		489	·001938	
775	·002379		383	·001779	
664	·002203		194	·001462	
564	·002056				

TABLE XVII.—On the Law of Thermal Radiation.

Heat received by the Bolometer; Sensitive Surface coated with Platinum Black; Temperature of the Bolometer, 17° C. (See figs. 10 and 11.)

4th May, 1898.		9th May, 1898.	
Temperature.	Mean corrected readings.	Temperature.	Mean corrected readings.
° C.		° C.	
511	4·9	1197	115·2
665	12·9	1121	91·1
716	16·6	1014	62·4
768	22·6	939	46·8
830	29·8	765	22·3
899	40·6	657	11·9
968	53·4		
1050	74·3		
1117	96·4		
1224	144·0		

Radiation received from palladium at its melting point . .	Radiator No. R_{27} . . .	407
	„ No. R_{28} . . .	396
Radiation received from melting platinum	Radiator No. R_{29} . . .	830
	„ No. R_{24} . . .	804

Heat received by a Thermopile, the Sensitive Surface of which was coated with Lamp Black.

Temperature.	Corrected galvanometer deflection.
° C.	
1166	97·8
1059	72·7
900	41·8
635	11·2

TABLE XVIII. (See figs. 12 and 13.)

Temperature.	Intrinsic brilliancy of surface in candle-power per sq. centim. of projected area.	Calculated temperature $(t-400) = 889{\cdot}6\sqrt[6{\cdot}9]{b}$.	
°C.			
1036	·0677	1002	November, 1897. Enclosure at about 15° C. Projected area of radiator ·4256 sq. centim.
1076	·131	1063	
1140	·250	1128	
1189	·437	1189	
1132	·231	1119	
1240	·735	1251	
1286	1·14	1307	
1360	1·96	1381	

	Temperature.	Intrinsic brilliancy of surface in candle-power per sq. centim. of projected area.	Calculated temperature $(t-400) = 889{\cdot}6\sqrt[6{\cdot}9]{b}$.
	°C.		
Radiator No. R_{23}	1500	4·15	1509
,, No. R_{24}	1500	4·95	
,, No. R_{21}	1779	20·53	1766
,, No. R_{22}	1779	18·00	

Fig. 2.

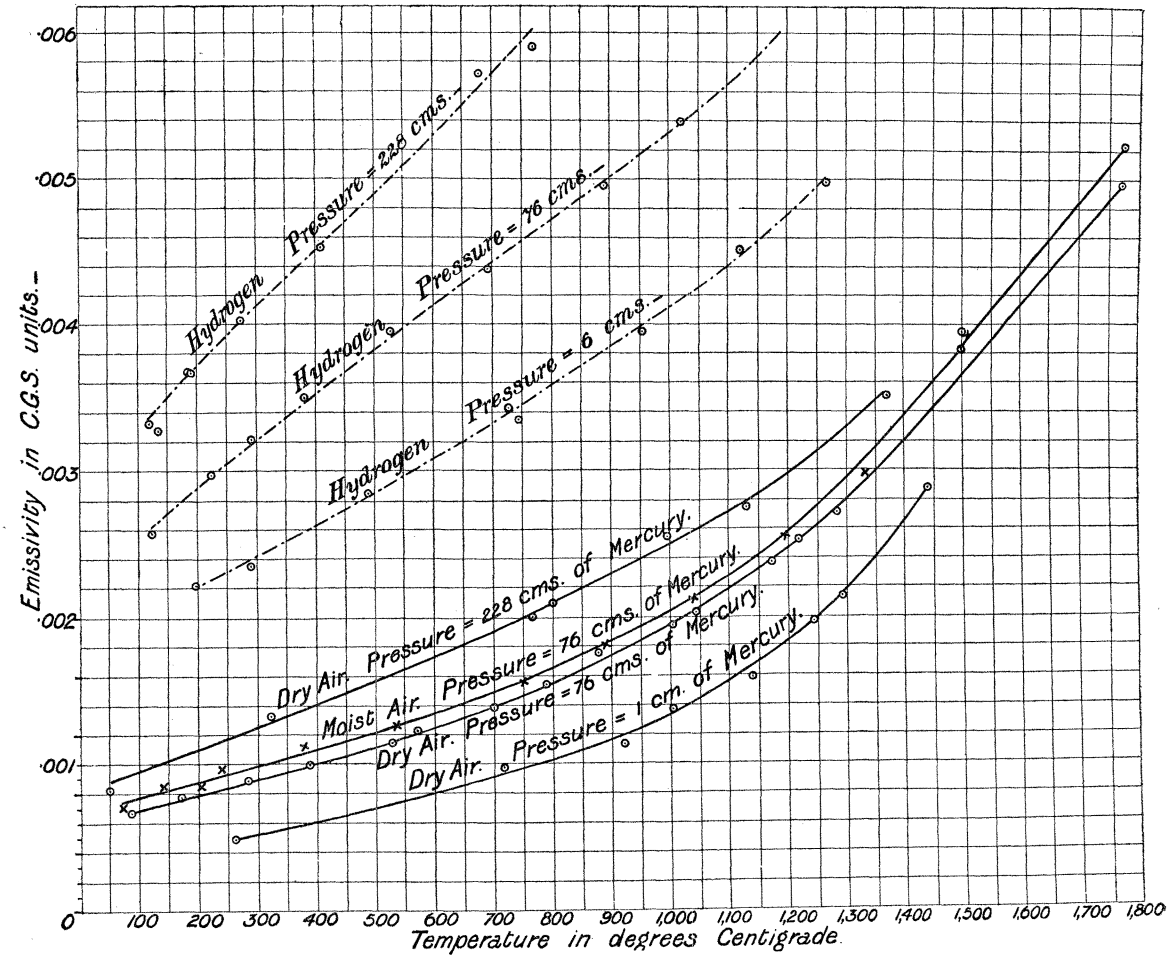


Fig. 3.

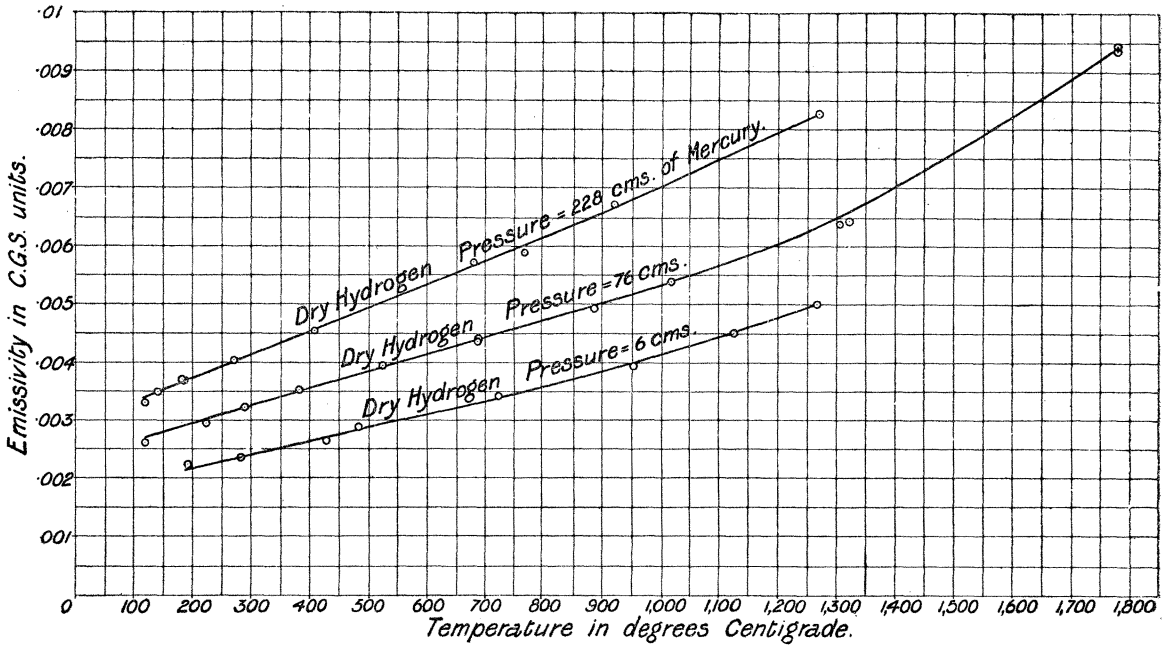


Fig. 4.

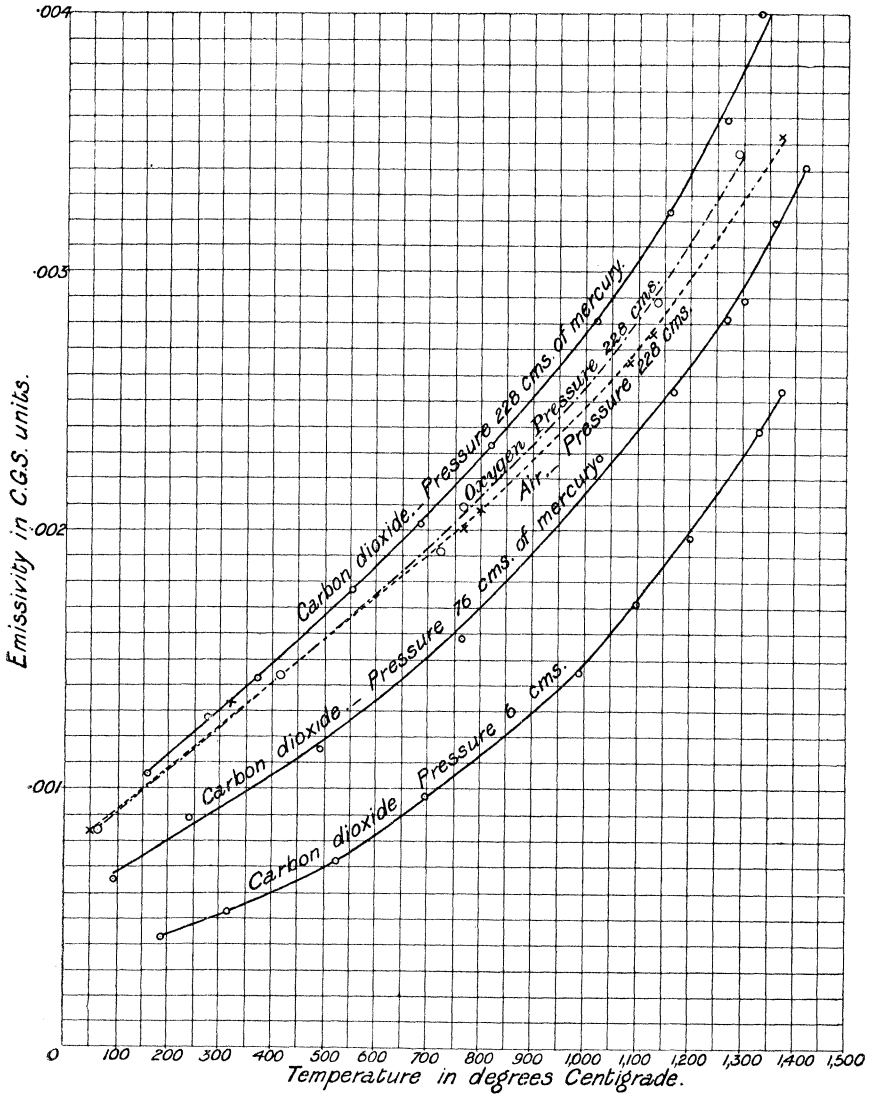


Fig. 6.

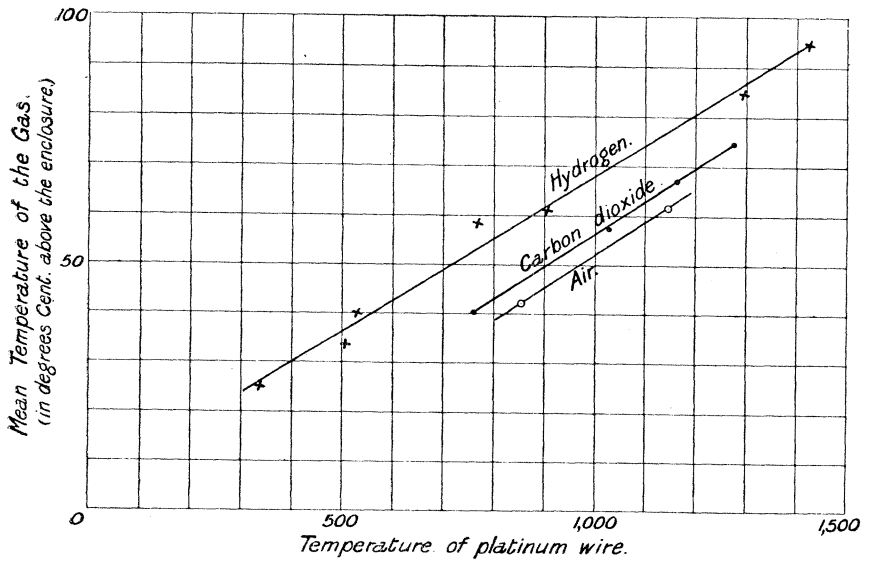
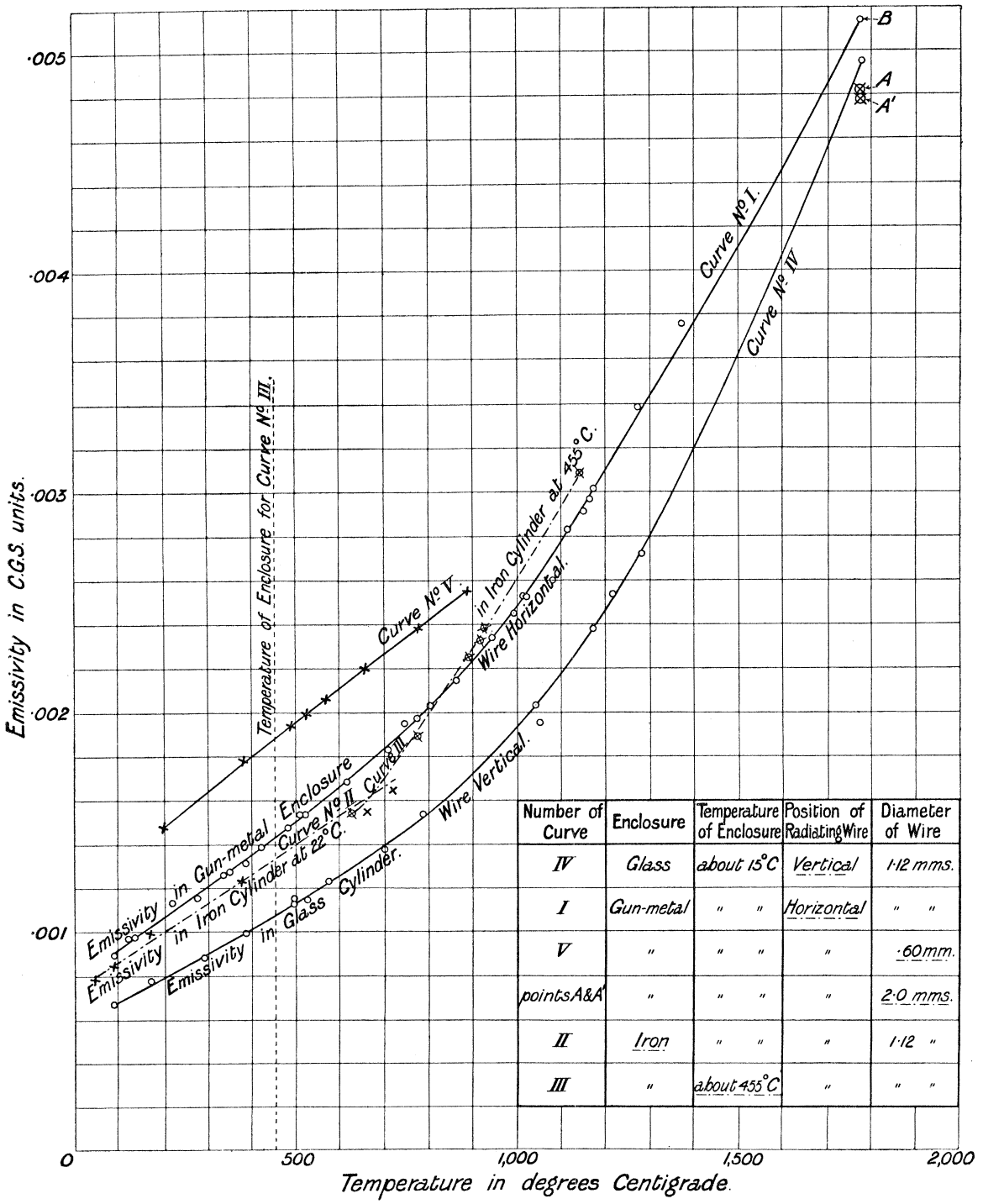


Fig. 7



Number of Curve	Enclosure	Temperature of Enclosure	Position of Radiating Wire	Diameter of Wire
IV	Glass	about 15° C	Vertical	1·12 mms.
I	Gun-metal	" "	Horizontal	" "
V	"	" "	"	·60 mm.
points A & A'	"	" "	"	2·0 mms.
II	Iron	" "	"	1·12 "
III	"	about 455° C	"	" "

Fig. 5.

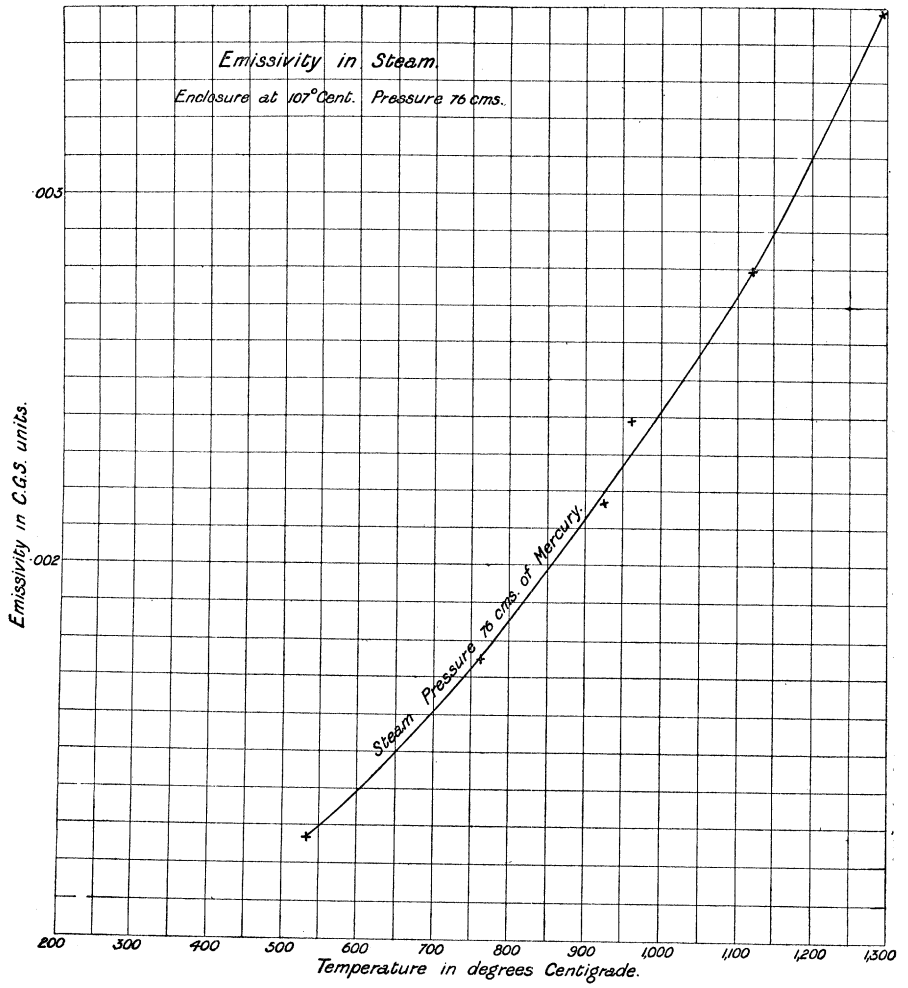


Fig. 10.

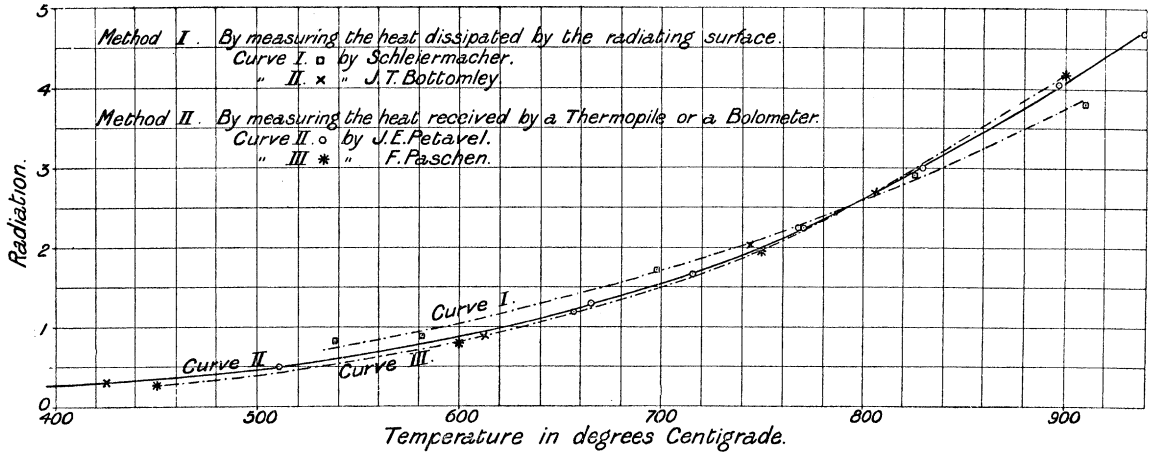


Fig. 11.

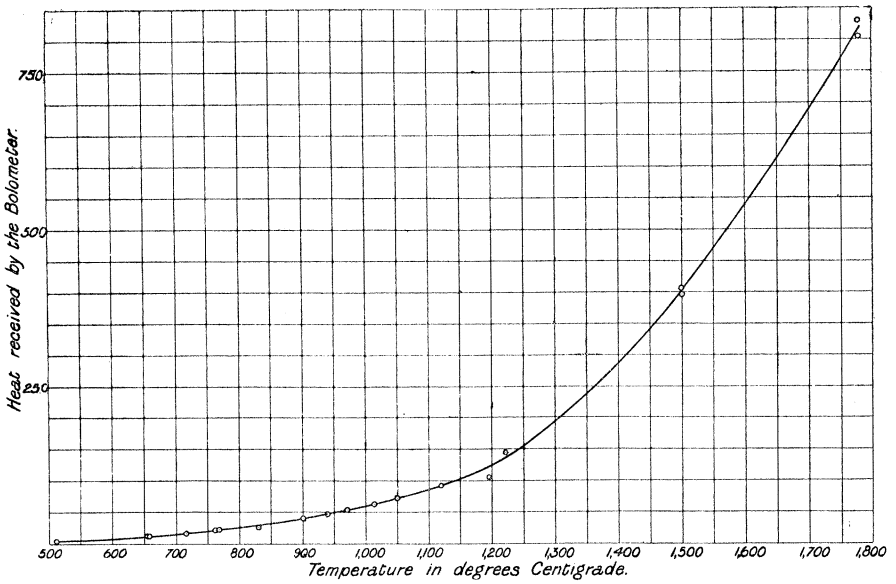
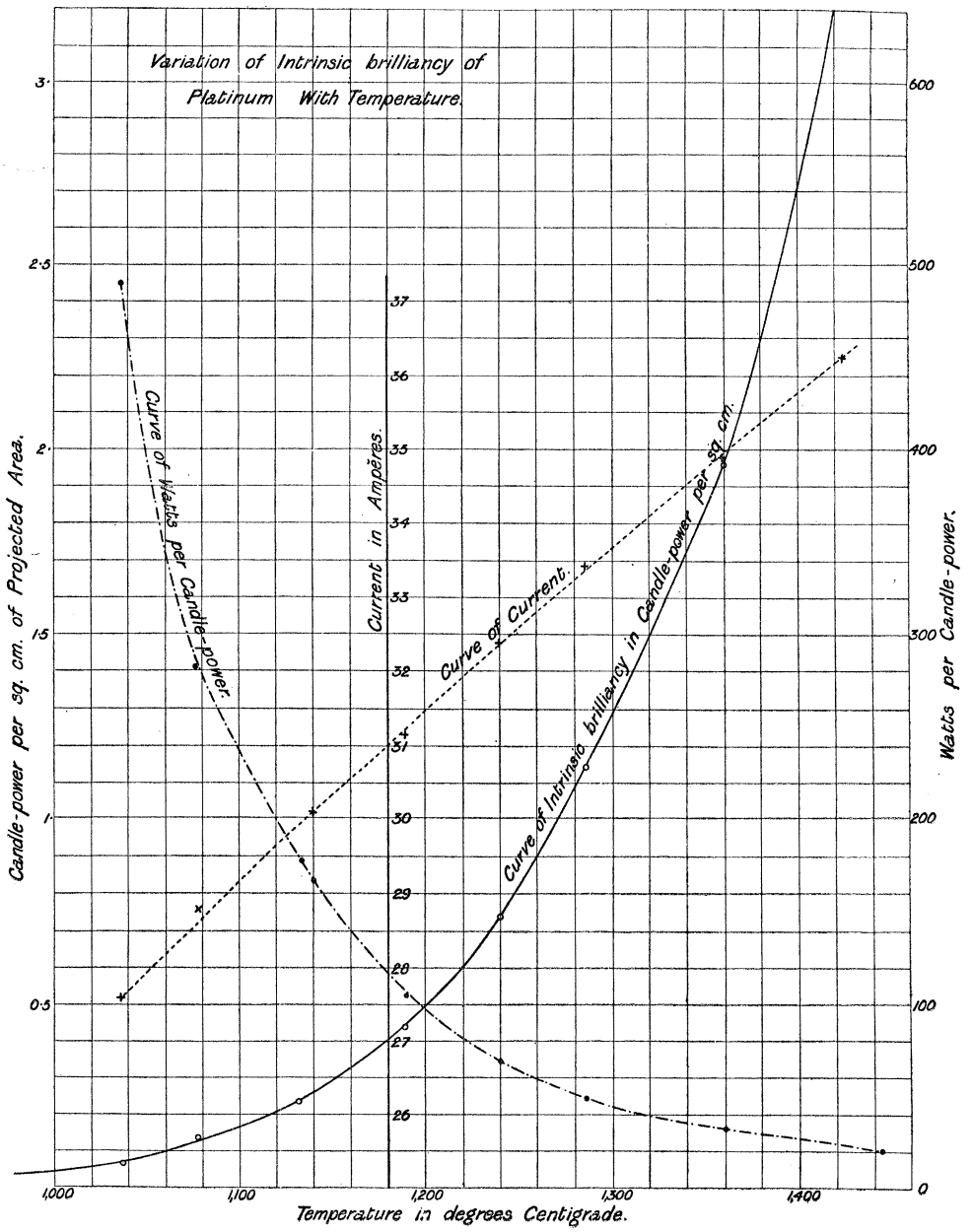
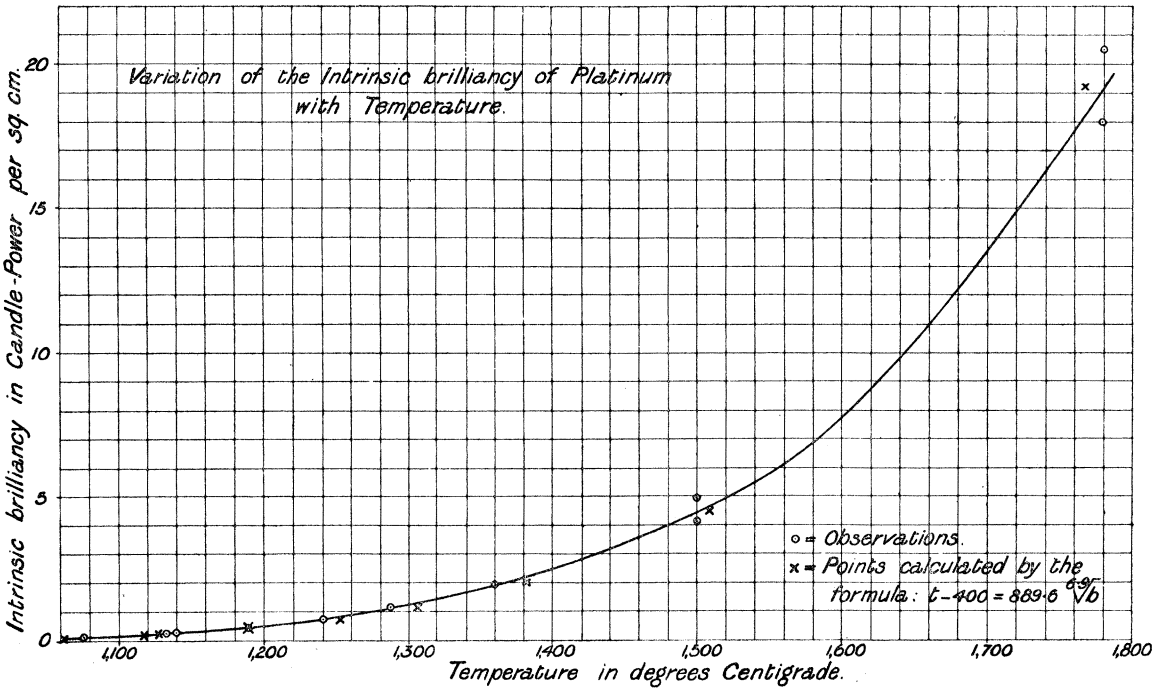


Fig. 12.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Fig. 13.



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